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Short communication

Test system design for Hardware-in-Loop evaluation of PEM fuel cells and auxiliaries

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Abstract

In order to evaluate the dynamic behavior of proton exchange membrane (PEM) fuel cells and their auxiliaries, the dynamic capability of the test system must exceed the dynamics of the fastest component within the fuel cell or auxiliary component under test. This criterion is even more critical when a simulated component of the fuel cell system (e.g., the fuel cell stack) is replaced by hardware and Hardware-in-Loop (HiL) methodology is employed. This paper describes the design of a very fast dynamic test system for fuel cell transient research and HiL evaluation. The integration of the real time target (which runs the simulation), the test stand PC (that controls the operation of the test stand), and the programmable logic controller (PLC), for safety and low-level control tasks, into one single integrated unit is successfully completed.

Keywords: PEM fuel cell; Dynamic test stand; Simulation; HiL; SIMULINK™; LabVIEW™

1. Introduction

In order to test or evaluate the dynamic behavior of proton exchange membrane (PEM) fuel cell stacks, or their auxiliaries, the dynamic capability of the test system must exceed the dynamics of the fastest component under test. Meeting this criterion ensures that when the fuel cell or auxiliary component is tested for a critical dynamic attribute (e.g., response time to a step function demand function), then the test system will not limit the time critical response of the unit under test (UUT), or affect the measurement.

This criterion is even more critical if a simulated component of the fuel cell system (e.g., the fuel cell stack) is replaced by hardware, as is the case when Hardware-in-Loop (HiL) methodology is employed. The response of the test system must then be sufficiently fast to allow the real time control of the test system to accurately reproduce the time behavior of the UUT. This requires an extremely fast acting test system.

To achieve such a highly dynamic test system response, an optimized test system and real time simulation device combination is designed and discussed. The core of this real time simulation and test system is an embedded real time (RT) controller, which is capable of both running a real time simulation and simultaneously controlling the complete test stand (including safety critical circuits) with the required dynamic capability. By utilizing state-of-the-art controller hardware, e.g., field programmable gate arrays (FPGAs), software tools for embedded application development (LabVIEW™ [1]), and dynamic simulation development tools (SIMULINK™ [2]), the basic elements of an HiL test system with unparalleled dynamics are demonstrated.

Multiple suppliers and designs of fuel cell stack testers exist in the market. This provides a choice of different system designs for stack testers, as well as manifold software control approaches. However, the available standard testers are actually designed for static or quasi-static testing, with an overall time constant of 10 s or more and typical dwell times of 10–20 min for measurement of a single current–voltage point. Custom designed (so-called “one-off”) dynamic test stands are faster and are able to achieve time constants of a few seconds. However, this is still inadequate to meet the dynamic criterion of being faster than the response of any component, or variable, within a fuel cell power system. As shown in the transient response study of Yana et al. [3], after only 400 ms a PEM fuel cell system already operates at a current density of 90% compared to the steady conditions at this operation point.

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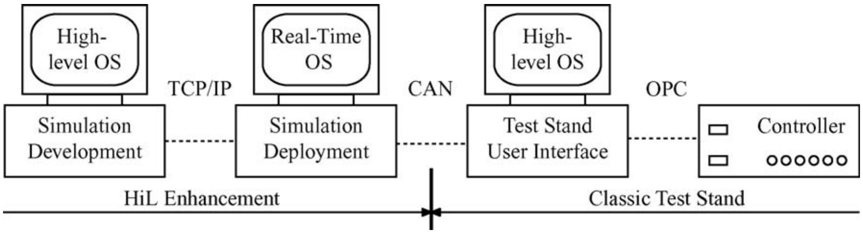

Fig. 1. Chain of controllers of a typical HiL system.

In order to achieve this time response criterion it is useful to answer the following question. How can the required time response be classified and analyzed in order to identify the limiting factors and effectively focus the search for improvement onto the critical elements?

To test a fuel cell stack, or implement HiL methodology, a chain of controlling devices is required to develop the simulation, run the simulation, and control the vital functionality of the test stand hardware. This design is illustrated in Fig. 1.

The classic approach for a fuel cell HiL system design, using a "plug-in" architecture, is to upgrade a conventional test stand by adding a simulation controller with an appropriate data interface. This is definitely not an optimized design, from the point-of-view of integration, and, although the data flow is not usually the limiting element, this classic approach leaves considerable potential for improvement.

Several conditioning and supply aggregates are required to properly operate a PEM fuel cell. A typical arrangement is shown in Fig. 2.

The combination of a fuel cell stack with an aggregation of auxiliary components like air compressors [4] or fuel reformers [5] represents an overall system with a wide range of time behaviors, typically spanning 4–5 orders of magnitude. For example, at the extremes of time behavior, properties that involve heat transfer or mass transport are quite slow (seconds to minutes), whereas electric properties like load settings or current responses may be extremely fast (milliseconds to microseconds).

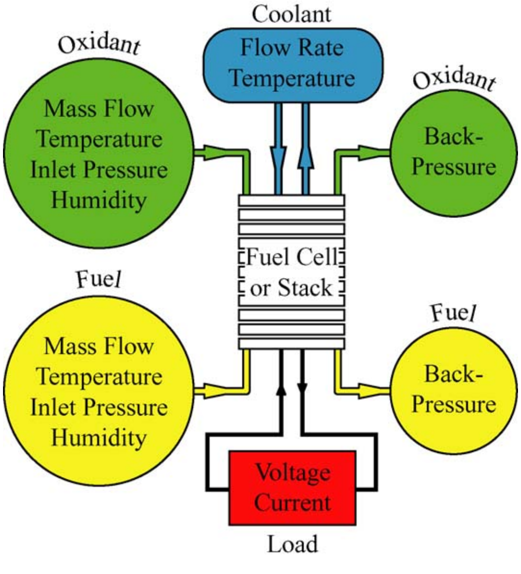

Fig. 2. Schematic diagram of a fuel cell system.

2. HiL with a test stand

Specialized systems for fuel cell testing with high sample rates and arbitrary, but yet predefined, load cycles have been realized [6] in order to verify models and life span investigation. Another common approach to dynamic testing or HiL evaluation is to combine a standard test stand with a simulation controller (Fig. 1). This is a conceptually simple approach and is supported by many test stand suppliers by providing a controller area network (CAN) interface to communicate with a real time simulation target. SIMULINK^{TM}, as a very popular simulation development platform, supports CAN communication via the real time target xPC^{TM} [2]. However, the use of the real time target risks losing the overall system determinism by communicating with a non-deterministic test stand computer, so this is not an optimum approach.

The CAN interface [7] sets an absolute limit to the data transfer of about 8 kByte s^{-1} using a low speed/fault tolerant bus, or 64 kByte s^{-1} on a high-speed bus. These rates are sufficient to allow, for example, 50 channels of double precision variables to be updated at 20 Hz, or for the high-speed bus, at 160 Hz. Reducing 8 Byte data precision to a measurement accuracy of usually 2 Byte (16 Bit ADC) and allowing a slower update rate for temperature measurement channels will improve transfer characteristics and push it beyond any limiting criteria.

Examining the auxiliary aggregates of a fuel cell system (Fig. 2), it is possible to separate the input/output ports into three distinct groups, based on typical time constants. Group 1 includes fast response transducers and controllers, e.g., cell voltage and current measurements as well as load control. Group 2 includes slow response transducers and controllers, which are not necessarily addressed at high rates, e.g., cell electrode temperature or gas inlet temperature.

Temperature characterization might be important for diagnostic fuel cell research (e.g., analysis of gas distribution), but is inherently restricted by heat capacity of the mechanical components and strongly linked to the design and materials of the UUT. HiL evaluation of a fuel cell stack or auxiliary component usually tests the dynamic response of the UUT for a specific application. For example, this may be an evaluation of a fuel cell stack within an environment like a fuel cell powered vehicle, which does not attempt a rapid change of temperature set points.

The third group of input/output ports for Fig. 2 accumulates parameters which are difficult to control at high rates but are subject to fast transitions for key applications. This group includes oxidant (air or oxygen plus water vapor) and fuel (hydrogen or reformate plus water vapor) mass flow, pressure and humidification. This group of system variables is the primary target for improvement in the dynamic HiL applications discussed in this paper.

3. Structural improvement

Bridging the interface between the standard fuel cell test stand use and real time simulation can be achieved by replacing the real time target, the test stand control PC and the integral (PLC) by a single PCI extension for instrumentation (PXI)-system as illustrated in Fig. 3.

PXI is an international industry standard for rugged, reliable PC based measurement and control systems. The embedded PC, running a skeleton real time operating system, is capable of controlling the test stand by direct communication with measurement and control hardware via a broadband PXI bus. Simultaneously, the high-speed decision-making for vital circuits is running directly on a FPGA chip. Bypassing any CPU, it achieves unparalleled reliability and cycle times of down to some microseconds. More computational intense parts of the control software utilize the CPU of the embedded PC, which also runs the real time simulation.

By choosing National Instruments^{TM} LabVIEW^{TM} as the control software development tool and MATHWORKS^{TM} SIMULINK^{TM} as the simulation language, a seamless integration is achieved, due to a cooperative interface provided by the two software companies.

The simulation is segmented into logical modules (for easier maintenance) and is compiled into dynamic link libraries (dll). The control software, designed in LabVIEW^{TM}, is responsible for the overall test stand functionality, for the data exchange with hardware and remote visualization targets, and for calling of the embedded real time simulation. The source code and simulation software is compiled for use by the RT target.

The set points and parameters for both the core software and the real time simulation are changeable "on the fly," via TCP/IP connection to a remote workstation. To modify the model without structural change of the I/O ports, it is only necessary to create a new dll and copy it to the RT target. The update of the dll requires only a very short downtime for the system. A modification of the LabVIEW^{TM} code, or the I/O structure of the embedded simulation, requires a new software download to the RT target.

4. Controller improvement

As pointed out in Section 2, fast time response control of oxidant (air or oxygen plus water vapor) and fuel (hydrogen or reformate plus water vapor) gases is difficult, primarily because of the physical restrictions of mass transport of compressible media combined with the relatively sluggish behavior of industrial mass flow controllers. However, rapid control of these gas flows is mandatory for achieving the fuel cell stack power response needed for dynamic applications (e.g., automotive power use). Improving the time response of the anode and cathode gas flow, pressure, and humidity control is vital for evaluation of fuel cell systems and system components for highly dynamic applications.

4.1. Control characteristics

Fig. 4 illustrates a typical, generic closed loop controller set up.

The response time for a mass flow controller is generally in the range of 10 s down to less than 1 s. In contrast, the measurement of mass flow is much faster, especially by harnessing the Coriolis effect. However, for a classic proportional, integral and derivative (PID) controller, which depends on feedback response time, even an optimized design implies a considerable time lag and several iterations to achieve a specified accuracy. By tuning some more "aggressive" PID parameters the reaction time can be lowered, but oscillation of the regulated condition can result.

A promising alternative is to utilize simulation. If the behavior of the test stand is reasonably well understood, and the UUT is at least predictable within a certain range, a model of the controlled system can be designed. Utilizing a strong non-linear control algorithm, like a model or a parametric mapping, the result is a faster, yet much more stable, controller characteristic. In order to manage the uncertainty of the system description, resulting primarily from the UUT, a classic PID design with larger time constants can be overlaid on this "feed forward" control scheme to eliminate small deviations and drift effects. Since the required agility of the PID controller is now low, a generic design is sufficient.

4.2. Control structure

In general, anode and cathode gas supply is specified not only by the required mass flow, but also by the system pressure.

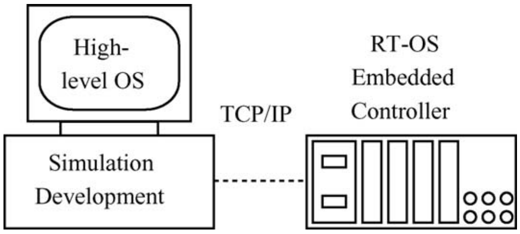

Fig. 3. Optimized controller configuration.

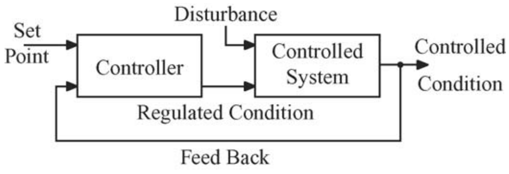

Fig. 4. Typical closed loop control design.

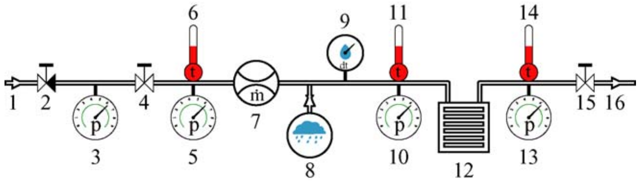

Fig. 5. Open design gas supply controller.

Though some fuel cell stacks operate at ambient pressure (with an open, vented outlet), most commercial stacks are operated under pressure (to increase performance metrics, such as power density). Typically, a closed loop backpressure system is used to establish the desired backpressure.

However, the mass flow and system pressure are physically linked by the geometry of the stack and, as a result, the control of mass flow and pressure cannot be done independently. When control of these mutually dependent variables is accomplished only at low controller speed, and therefore strong damping, cross talk between controllers is insignificant. However, a faster and more reactive system will be subject to the dependency of the two variables. This can result in control instability associated with "hunting" by the two independent controllers, resulting in oscillation of the gas mass flow and gas pressure. This can be prevented by designing a compound system.

Fig. 5 shows an open control design where an adjunctive set of valves (Table 1, Positions 4 and 15) establish both the desired mass flow and the system pressure. A common controller evaluates the valve position by gathering all required measurement data from the transducers and utilizing the analytic system model, or utilizing empirical data maps as needed. This comprehensive design uses primarily a forward approach to calculate the set points from well-known initial conditions.

The overlaid, and weaker, feedback regulation limits the system uncertainty, fine-tunes the system conditions, and prevents any small unaccounted disturbances from causing drift effects. In general, the weighted combination of forward and feedback control algorithm achieves a faster system settling time with less hunting and iteration.

Table 1
Item descriptions

Position	Description
1	Gas inlet
2	Check valve
3	Gas pressure
4	Inlet control valve
5	Regulated pressure
6	Gas temperature
7	Mass flow
8	Steam injection
9	Dew point sensor
10	Cell inlet pressure
11	Cell inlet temperature
12	Fuel cell
13	Cell outlet pressure
14	Cell outlet temperature
15	Backpressure control valve
16	Gas exhaust

5. Results

A feasibility study has been successfully completed for the conceptual design of a dynamic test system for fuel cell transient research and HiL simulation. The integration of the real time target (which runs the simulation), the test stand PC (that controls the highest level operation of the test stand), and the PLC (for safety and low-level control tasks) into one single integrated unit was successfully completed. A core hardware component of the study is a National Instruments PXI system, described in Table 2.

In order to evaluate and demonstrate the benefits of the new design study, a fuel cell vehicle simulation was selected. Vehicle applications are among the fastest for fuel cell employment and, because of their large prospective impact on ecologically sound transportation systems, are widely used in simulations [8] and HiL testing [9,10].

Because of the modular and clearly structured organization, FCVSim [11] was the simulation tool of choice. It is a fuel cell vehicle simulation implemented in SIMULINK^{TM} with already approved performance when running Windows operated PC. For this demonstration, the FCVSim simulation is compiled into a real time dll and is then embedded into a LabVIEW^{TM} program. The LabVIEW^{TM} program manages data exchange with a remote PC for visualization of the results as well as signal output via the hardware I/O ports. After downloading the source code to the PXI-controller, the real time simulation successfully runs and generates set point signals for fuel (hydrogen) and oxidant (air) demand. A time sequence of typical set point signals are presented in Fig. 6, using the Federal Urban Drive Schedule (FUDS) driving cycle for the FCV application simulation.

Using the remote PC, various drive cycles were uploaded to the real time target and actual parameters of the simulation were updated "on the fly" (e.g., see Fig. 7 for a typical result). For the FCVSim simulation, a timeframe of 5 ms was achieved and the evaluation of the concept design for a dynamic HiL implementation was successfully demonstrated.

6. Next steps

To prove the concept of an open-design gas supply controller, a downscaled set up is currently under investigation. The same

Table 2
PXI system component listing

Unit description	Type no.
Four-slot PXI chassis	PXI-1002
2.2 GHz P4 embedded controller	PXI-8186
Reconfigurable I/O FPGA board	PXI-7831R
1.2 MSample/second multi I/O board	PXI-6070E
80 MHz timer/counter board	PXI-6602

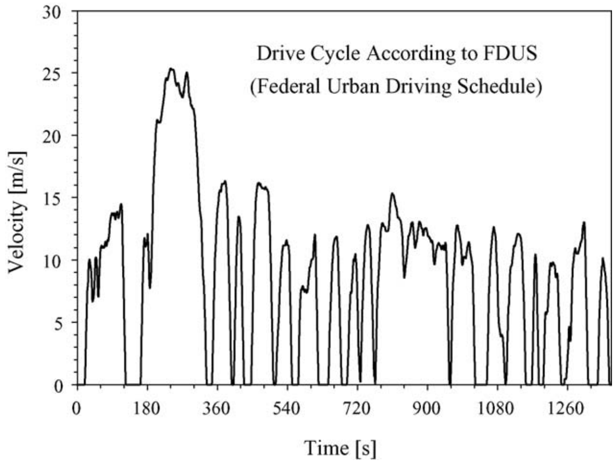

Fig. 6. FUDS drive cycle.

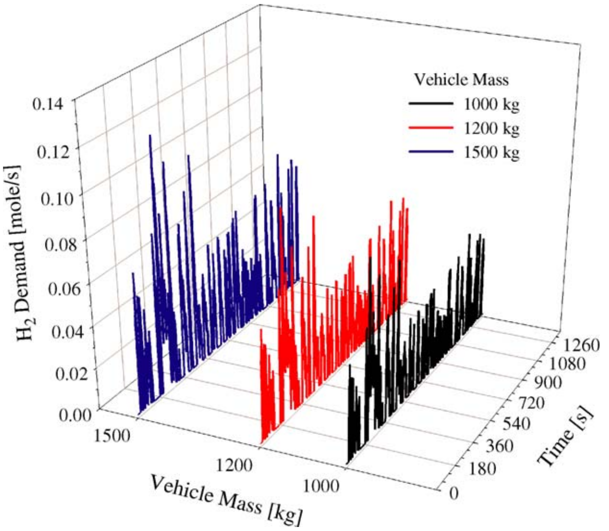

Fig. 7. H_2 demand as a function of vehicle mass.

test hardware as described in Table 2 is used, mainly the FPGA circuitry.

The first measurements with a mapping-based forward algorithm, in combination with a weighted PID overlay, show a significant improvement when compared to a conventional, generic PID controller. A model based algorithm, or even an embedded simulation, will be employed the next steps in this study.

This approach will be implemented on a more complex test set up to demonstrate the concept on a complete and fully functional fuel cell stack gas supply train.

7. Conclusions

The analysis of a conventional HiL approach for PEM fuel cell stack evaluation, and transient research, identified the inherent weakness of a test system design using add-on architecture with a standard test stand. This design distributes the simulation and test stand control to multiple machines and causes an unnecessary complex hierarchy of controllers and communication structures, leading to a system that is susceptible to non-deterministic behavior and unacceptable time delays. A similar drawback applies for the control of the time critical oxidant and fuel gas supplies. The result is a prolonged settling time, plus the potential hazard of instability—especially if the damping factors are decreased in an attempt to improve the performance of this non-optimized controller strategy.

The basic concept of integrating the data processing devices and the fuel and oxidant supply controllers has been evaluated, and the basic design utilizing this concept has been evaluated in this paper. This concept promises improvement to the overall performance and the realization of an unparalleled and fast acting testing system for PEM fuel cell stack research, dynamic testing, and HiL evaluation.

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