

Fuel cell hardware-in-loop

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Abstract

Hardware-in-loop (HiL) methodology is well established in the automotive industry. One typical application is the development and validation of control algorithms for drive systems by simulating the vehicle plus the vehicle environment in combination with specific control hardware as the HiL component. This paper introduces the use of a fuel cell HiL methodology for fuel cell and fuel cell system design and evaluation—where the fuel cell (or stack) is the unique HiL component that requires evaluation and development within the context of a fuel cell system designed for a specific application (e.g., a fuel cell vehicle) in a typical use pattern (e.g., a standard drive cycle). Initial experimental results are presented for the example of a fuel cell within a fuel cell vehicle simulation under a dynamic drive cycle.

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1. Introduction

Fuel cell system and fuel cell vehicle (FCV) simulation are standard techniques in the FCV and system design development process. Today the application of simulation techniques primarily supports the analysis of different concept system configurations (hybrid versus load following, component size and arrangement, etc.). FCV simulation assists in the early vehicle development phase as part of the process of seeking an optimal concept configuration that meets the minimum or desired application requirements. In practice, the minimum requirements of the proposed vehicle configuration (range, fuel efficiency, acceleration, top speed, payload, etc.) are defined, set as targets, and the concept configurations are evaluated by the method of numerical simulation.

For concept development at the beginning of the FCV development process, a number of different simulation tools are available today and have been benchmarked [1]. It was found that, in general, the available tools could be separated into two general groups, one group of tools with a non-causal approach

and a second group of tools based on a causal approach. While the “non-causal” tools require less computational resources, the inherent non-causality in this group of models cannot support applications in the rapidly expanding field of system evaluation and validation through hardware-in-Loop (HiL) and rapid prototyping (RP) methodologies. In contrast, although the causal tools require significantly higher computational resources they are required for detailed dynamic FCV simulation (at the subsystem and component level), and are absolutely necessary for the development of HiL methodologies.

This paper describes the adaptation of a dynamic FCV simulation tool for application to fuel cell HiL for dynamic system applications, reviews the development of the initial experimental HiL tool, and applies this tool to an example fuel cell system and vehicle application. This is the first step toward establishing a general fuel cell HiL methodology.

The Hawaii Natural Energy Institute (HNEI) of the University of Hawaii has designed and installed a dynamic fuel cell test system with the goal of demonstrating the concept of fuel cell HiL as a general tool for the development and evaluation of fuel cell components and system designs in highly dynamic applications—e.g., automotive traction power within a FCV. The fuel cell test system dynamic response (pressure, flow, humidification, etc.) required for the FCV application is ~ 1 s, ca. 3 orders of magnitude faster than the values

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typically used for static fuel cell testing (e.g., 10–20 min per $V-I$ pair).

The initial hardware-in-loop implementation (HiL #1) was commissioned at HNEI in January–February 2006 and is currently in operation at the Hawaii Fuel Cell Test Facility. HiL#1 is being tested and modified to establish the capability for evaluation of the transient response of fuel cells in dynamic applications.

This paper describes the key elements of the HNEI hardware-in-loop concept, the structure and methodology underlying the step from simulation to HiL, and illustrates, by example, the extension of a FCV simulation tool into an experimental HiL tool.

Experimental results are presented to demonstrate the capabilities of this new fuel cell HiL technique for FCV applications. This demonstration uses the simulation of a hydrogen FCV, standard international driving cycles, and a fuel cell as the HiL component.

2. Simulation methodology

This section outlines the methodology of a dynamic simulation tool for fuel cell passenger vehicles, *FCVSim*, and illustrates how it is adapted for the HiL methodology. The details underlying the *FCVSim* simulation tool have been presented in detail in literature [2–5], and will only be briefly reviewed here at a level sufficient to understand the HiL adaptation of this tool—the subject of this paper.

Fig. 1 shows the highest level structure of the *FCVSim* simulation tool, for a fuel cell passenger vehicle.

The “Driver” block of *FCVSim* represents the driver properties and driver characteristics. The main task for this block is the comparison of the driving cycle with the vehicle velocity. From a systems point of view, the driver can be viewed as the overall controller for the “Vehicle” (Vehicle Controls, Drive Train, Vehicle Body and Fuel Cell System). This is the highest level example of the strict separation of control functions from sub-system models in *FCVSim*, and this strict separation is required for the extension of *FCVSim* to HiL methodologies. The goal of the Driver block is to ensure

that the vehicle follows the drive cycle within a specified tolerance.

The inputs to the Vehicle Controls block are the acceleration and brake pedal positions and the output of the Vehicle Body block is the vehicle velocity. The acceleration pedal position feeds into the Vehicle Controls block. This block applies a control algorithm to achieve the appropriate acceleration command for the Drive Train block, which in turn determines the fraction of the maximum motor torque that is supplied to the vehicle wheels. The brake pedal position also feeds into the Vehicle Controls block. This block separates mechanical braking and regenerative braking (in hybrid vehicles only) functions. The request for regenerative braking is applied internally within the Drive Train block and also controls the motor torque applied to the Vehicle Body block, whereas the request for mechanical braking is fed directly to the Vehicle Body block, thereby controlling the use of the mechanical brake system model.

The Drive Train block includes models of: (1) the power electronics for the electric motor, (2) the electric motor, (3) the transmission, and (4) the controls for the electric motor and the transmission. Depending on the driver request, as expressed by the acceleration and brake signals, the Drive Train block provides torque to the wheels and draws current from the Fuel Cell System block.

The Vehicle Body block models the mechanical properties of the vehicle (aerodynamic drag, rolling resistance, mass, etc.). The inputs into this block are the applied wheel torque and the signal for the mechanical brake fraction. The outputs are the resulting vehicle velocity and motor speed. In designs not considering tire slip, and using a one-speed transmission, these two output values are directly correlated, and it is this case that is shown in Fig. 1.

The Fuel Cell System block in Fig. 1 includes models of the components of the fuel cell system and the associated control functions for both the individual components and the overall system, as required for any specific system design. For example, in the case of a hybrid design, the Fuel Cell System block will also include an energy storage device (e.g., a battery and/or ultra-capacitor) and associated control functions. Alternatively, in the case where hydrogen fuel is not carried onboard, the Fuel

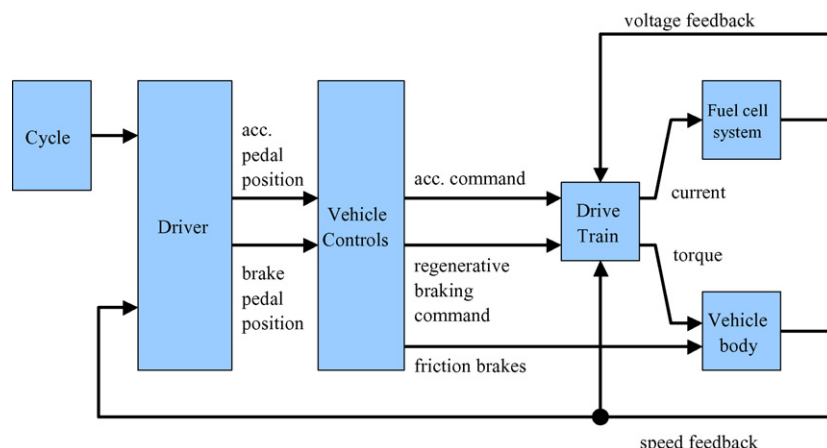


Fig. 1. Structure of existing fuel cell vehicle simulation tool, *FCVSim*.

Cell System block will include a fuel reformer and associated controls and, of course, could also be hybridized with energy storage.

The input to the Fuel Cell System block is the electric current demanded by the power electronics controller to supply the electric motor. The output of the Fuel Cell System Block is the voltage provided by the fuel cell system to the power electronics at the demanded current. For the case of a non-hybrid FCV this is frequently the same voltage as the fuel cell stack voltage (although a voltage boost converter may be used), and varies significantly with current demand. In hybrid designs this voltage may be the battery voltage, or any other voltage, depending on the exact fuel cell system design and particularly depending on the location of the dc–dc converter that is normally used in hybrid designs (i.e., the fuel cell stack voltage is generally modified by the hybrid design and control strategy).

A key attribute of the highest level structure for *FCVSim* is that it incorporates two major physical feedback loops that simulate the physical dependence of the maximum motor torque of the electric drive train on the voltage supply and on the motor speed (see Fig. 1). The physical origins of these feedback effects are:

- **Mechanical feedback:** If the driver requests an increased torque (i.e., depresses the accelerator pedal) the electric motor speeds up and the drive train provides an additional torque to the wheels. Because of this torque supply the vehicle accelerates along with the motor speed increase. This increase in motor speed feeds back to the Drive Train block, to account for the dependence of the motor torque on motor speed.
- **Electrical feedback:** As soon as the motor starts spinning it provides mechanical torque to the wheels. It can only do this by drawing electrical power from the Fuel Cell System block. For example, when the motor draws an increased electric current from the fuel cell system the voltage generated by the fuel cell system, and provided to the dc terminals of the power electronics, decreases as the load current increases and is also dynamically dependent on the fuel (e.g., hydrogen) and air

flow properties provided to the fuel cell stack by the fuel and air subsystems within the fuel cell system. To account for the dependence of the maximum motor torque on the supply voltage, this decreased voltage is fed back to the electric drive train as a dynamic input.

The voltage variability effect associated with the electrical feedback loop can be particularly dramatic for a fuel cell power system, depending on the exact state of the air and fuel supply relative to the current (power) demand. Accounting for these effects is a critical requirement in providing a realistic dynamic simulation of any FCV, and it is this electrical feedback effect that is utilized in adapting *FCVSim* to our fuel cell HiL methodology.

These two major feedback effects at the highest level of *FCVSim*, together with the physical component characteristics, determine the overall dynamic characteristics of the combined drive train, power source and vehicle. The setup of *FCVSim* is analogous to the physical setup of a real vehicle. This logical structure within the simulation tool is another key attribute that enables the basic *FCVSim* tool to be adapted for the HiL application.

3. Adaptation of the *FCVSim* tool for HiL applications

As an example of the adaptation of the *FCVSim* tool for a HiL application the simplest FCV system (i.e., a direct-hydrogen load-following FCV design) is used.

A controls engineering view of the direct-hydrogen fuel cell system is provided in the literature [2], and a detailed exposition on the fuel cell system simulation for the direct-hydrogen FCV is also available [6]. Fig. 2 illustrates the physical configuration of the direct-hydrogen fuel cell system within the load-following version of *FCVSim*, but without explicitly displaying control functions for the fuel cell system or for the individual subsystems or components.

There are four major subsystems illustrated in the direct-hydrogen fuel cell system of Fig. 2. These subsystems are:

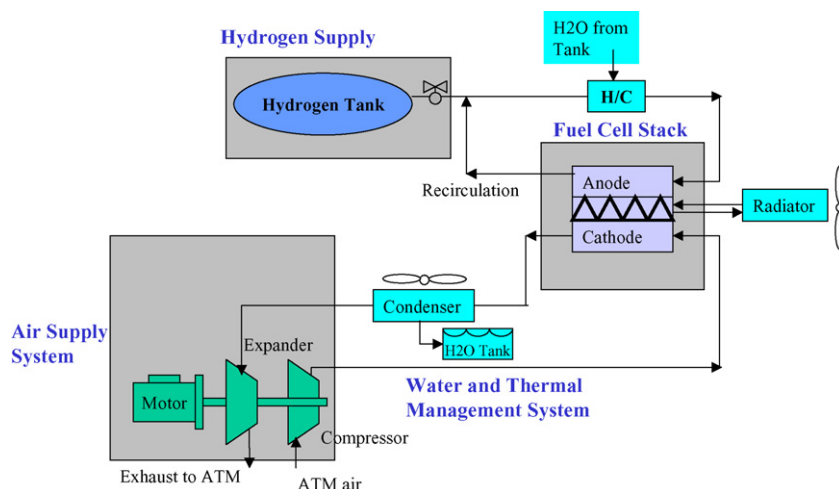


Fig. 2. Direct-hydrogen fuel cell system diagram.

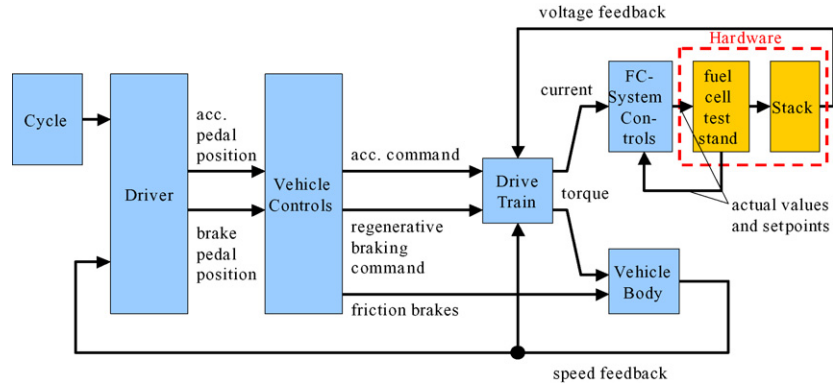


Fig. 3. HiL shown as the replacement of the fuel cell system model through hardware.

- fuel cell stack;
- hydrogen supply;
- air supply system;
- water and thermal management system.

Each of these subsystems requires component models and sub-systems control simulations within *FCVSim*.

The behavior of the fuel cell (or stack) and the fuel cell system is one critical element in a dynamic FCV simulation. To experimentally evaluate the performance of the fuel cell in this application, the HiL adaptation of the direct-hydrogen version of the *FCVSim* tool replaces the simulated fuel cell by an actual fuel cell.

The air system, the fuel supply system and the cooling system are controlled by the simulation but are realized in hardware through a simulation-based control of the dynamic fuel cell test system.

This adaptation is illustrated further in Fig. 3. In this figure a real fuel cell (or stack) is operated in combination with a dynamic fuel cell test system and an electronic load. The dynamic cell test system provides the required hydrogen, air, water, and heat to the cell—and provides control functions for the cell (or stack) and

fuel and air supply, water and thermal management, depending on the set-points demanded by the simulated FC controls.

In the configuration illustrated in Fig. 3, the remaining elements of the original FCV simulation tool calculate the actual control set-point for the electronic load, i.e., the current demand (the surrogate for the fuel cell system power). Based on the value of this current set-point, the FC system controls of the simulation determine the set-points for fuel and air supply, humidification and the cooling system. The fuel cell (or stack) hardware responds with a real voltage signal, which is fed back into the simulation through the voltage feedback loop (as discussed above in the description of the *FCVSim* structure) and this actual experimental dynamic voltage variation is then utilized within the simulation (in place of the simulated fuel cell system voltage response illustrated in Fig. 1). New set-points are then generated by the *FCVSim* vehicle simulation, as required by the drive cycle, and these new set-points are provided to the dynamic test stand as the basis for the next step in the HiL process.

For HiL implementation, the dynamic test system is connected via a controller area network (CAN) interface to the *FCVSim* simulation software, adapted as discussed above (i.e., with the fuel cell simulation replaced by an actual fuel cell test

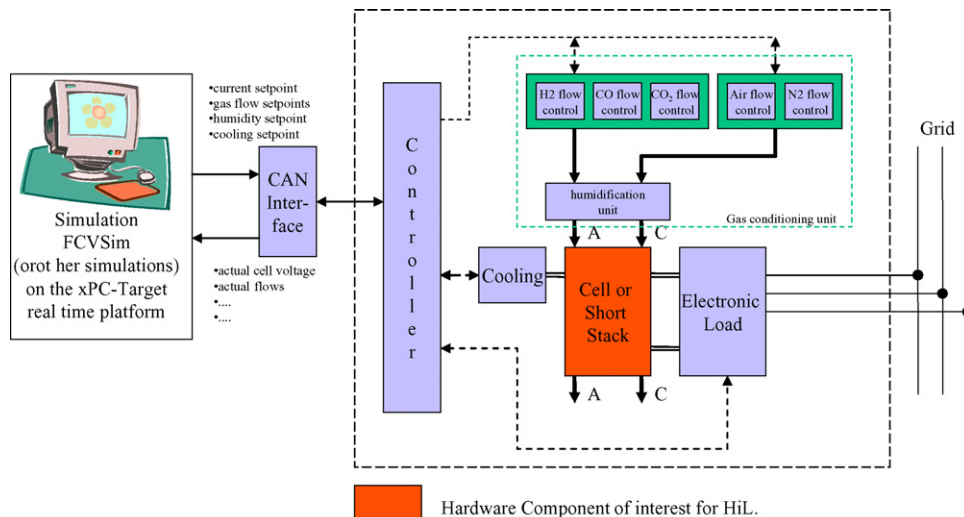


Fig. 4. Interface of the simulation software with the existing hardware test stands.

object). This configuration is illustrated in Fig. 4, and it is this concept configuration that is utilized for the initial realization of the HiL capability presented in this paper. In Fig. 4 a general fuel supply configuration is indicated, to allow for simulating the use of a fuel reformer (i.e., including the possibility of combining CO and CO₂ with hydrogen for the anode input), but in this paper only the pure hydrogen option will be used as an example.

Of course, the HiL methodology is not limited only to the replacement of the fuel cell and system simulation with hardware. The technique can also be applied to the drive train or to subsystems within the fuel cell system, e.g., the air compressor within the fuel cell system. Also, in the example discussed here (the fuel cell and system replacement with hardware) the current demand is not the only parameter that can be fed as a set-point from the simulation to the hardware to elicit actual experimental data responses. Other set-points of interest might be the cooling request for the fuel cell system (internal to the dynamic stack test system in the above illustration). A feedback for this request could be the actual fuel cell temperature or the temperature of the cooling liquid. In this case, for example, HiL would allow the investigation of cooling strategy/control and provides information about radiator sizing.

4. Applied software chain

For choosing the software tools applied in this project, several criteria were considered as important. These key criteria for the basic software tools are:

- commercially available (no in-house solutions);
- must be an industry standard, as closely as possible;
- have high flexibility;
- transparency and ease of use;
- seamless integration of HiL and RP features;
- scalability (easy entry with the possibility to move ahead to highly specialized development projects).

The software tool chain for the simulation portion of this project uses software toolboxes from The Mathworks, Inc. that incorporate all of the listed key criteria.

The fact that all of the selected simulation software tools are from one software supplier greatly simplifies the setup of new configurations and associated troubleshooting. The base products (Matlab and Simulink) are well known in industry and

educational applications. This choice of simulation software significantly reduces the time and cost of establishing the fuel cell HiL project. Also, the tools are flexible and a wide range of functionalities is supported through special toolboxes available from Mathworks. The additional possibility of the simple integration of C-code (S-Functions) also provides flexibility.

The control of the dynamic fuel cell test system is accomplished through the use of LabVIEW software available from National Instruments. The simulation and control software are integrated through an interface provided by the two software providers.

This choice of software tools provides a relatively simple entry into the field of HiL from established and widely practiced simulation and control software tools—Simulink and LabVIEW. The existing *FCVSim* tool is completely coded in Matlab–Simulink–Stateflow [7], and no additional toolboxes have been applied.

5. Initial experimental HiL results

Implementation of the initial fuel cell hardware-in-loop system (designated as HiL#1) is illustrated in Fig. 5.

This software plus hardware combination has as an objective the evaluation of the performance of a fuel cell test object under conditions that would exist in a fuel cell system within an FCV being driven over a test drive cycle. That is, to expose the fuel cell to the dynamic operating conditions (current demand, fuel and air flows, etc.) that it would experience in a fuel cell system within a FCV being driven over a dynamic drive cycle test. This capability will permit an initial evaluation (e.g., performance, durability, etc.) of any specific fuel cell technology—without the expense and time required for the development of actual system and vehicle hardware and actual drive cycle tests.

The purpose of the initial series of HiL tests was to verify successful operation of the HiL implementation in Fig. 5 through use of the previously developed FCVSim FCV simulation model (within the Host PC unit) via xPC Target with a CAN interface (within the Target PC unit). Once this communication was verified and established, a specific set of tests were conducted to provide proof-of-concept for the HiL configuration (HiL #1) illustrated in Fig. 5. These tests included the following:

- ability to send and receive values of all set points and data packages;

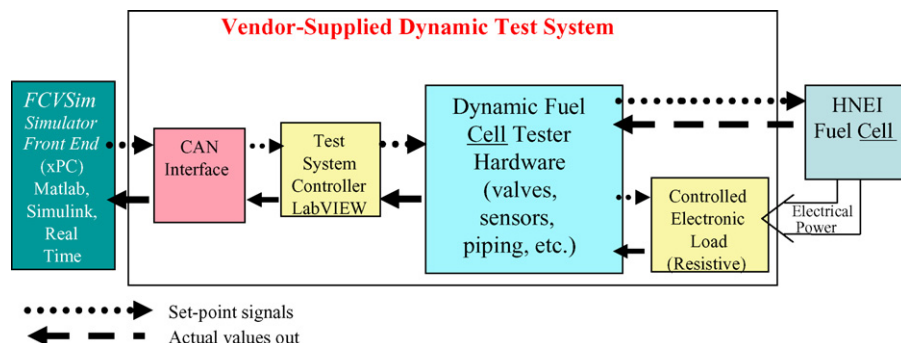


Fig. 5. Initial fuel cell hardware-in-loop System (HiL #1).

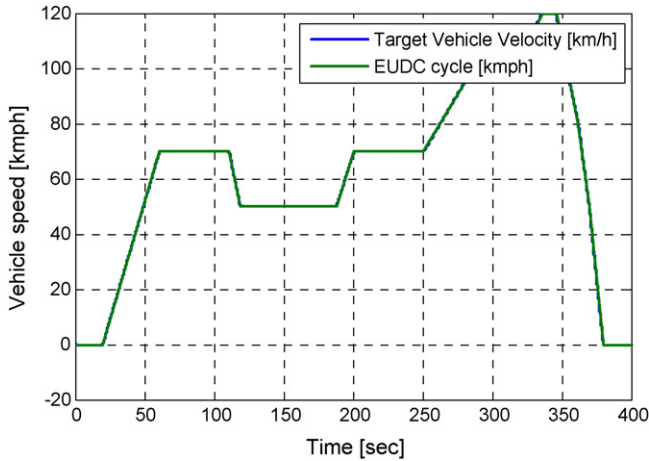


Fig. 6. EUDC and vehicle velocity from the Target PC screen.

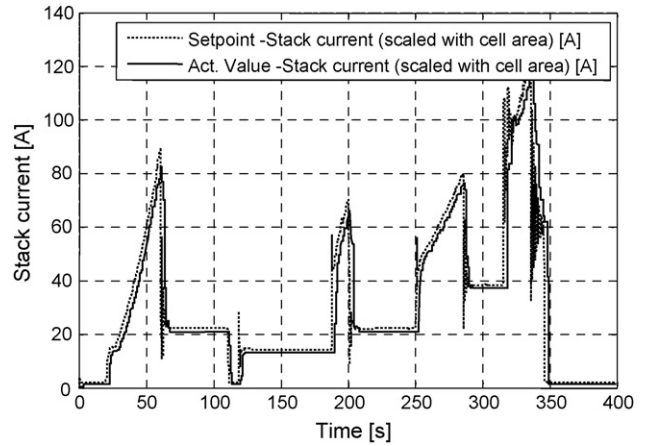


Fig. 7. Fuel cell stack current set points and actual values.

- integrating the dynamic test system with the simulation program;
- real-time FCV simulation stability during operation using the drive cycles;
- changing model parameters (e.g., vehicle mass, aerodynamic drag, tire friction) “on the fly” to evaluate the impact of such parameter changes.

One driving cycle used for running the *FCVSim* simulation program during the various portions of these initial HiL tests was the extra urban drive cycle (EUDC).

This drive cycle and the resultant vehicle velocities generated within *FCVSim*, operated in real-time, are shown in Fig. 6. The vehicle velocity coincides essentially exactly with the desired test drive cycle, on the scale used in this figure.

This desired velocity profile (drive cycle) is transformed by the real-time FCV simulation into a demand (set-point profile versus time) that is transmitted via the CAN Interface to the dynamic fuel cell test system. This demand is in turn translated by the dynamic fuel cell test system controller and hardware into actual values for fuel cell current, hydrogen flow rate, air flow rate, pressure, humidification, and so forth.

Figs. 7–9 present the experimental results obtained in these initial tests for the cell current, anode mass flow and cathode mass flow, respectively. The actual experimental data for each of these variables are shown vis-à-vis the real-time simulation set-points.

As can be seen from Figs. 7 to 9, the fuel cell HiL system is following the basic demands of the FCV simulation, as required by the EUDC drive cycle. The generation of real-time simulation set-points by *FCVSim* in this initial testing is performing properly and the dynamic fuel cell test system is translating these set-points into actual physical anode and cathode flows to the fuel cell test object.

However, there is evidence of “hunting” on the part of the anode and cathode flow controls and of delays, as well as undershoot and overshoot, between the set-points and the actual data responses. Further testing and analysis has determined that these artifacts are due to both software and controller limitations in

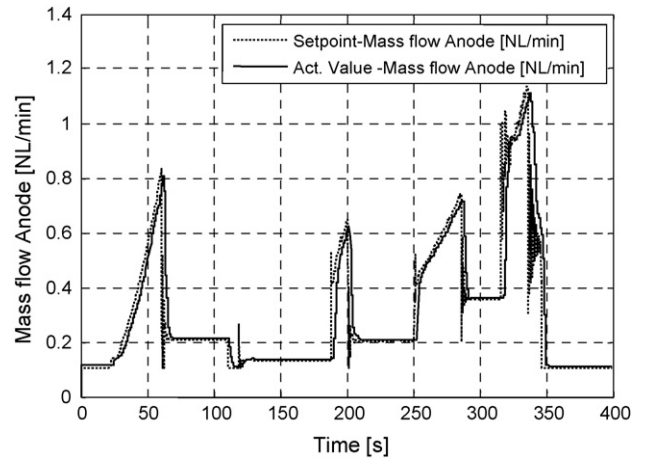


Fig. 8. Anode mass flow set points and actual values.

the Test System Controller provided by the dynamic test system vendor (see Fig. 5). Eliminating these artifacts through in-house software modifications and hardware modification and replacement is now underway as the next step in the development process for fuel cell HiL methodology and experimental capability at HNEI [8].

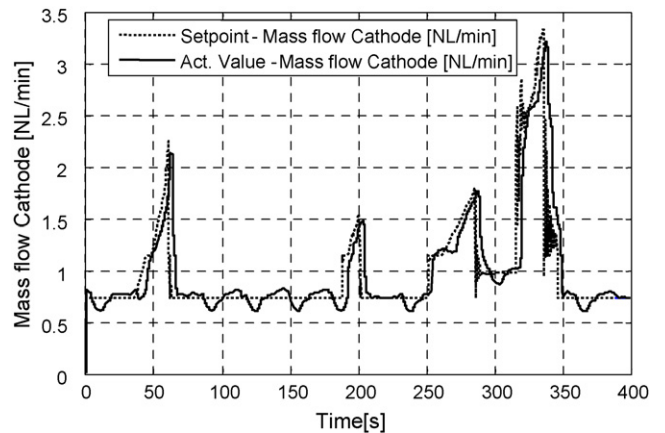


Fig. 9. Cathode mass flow set points and actual values.

When this HiL laboratory capability is complete, the HiL system and methodology will provide a complete environment for the analysis of fuel cells and fuel cell system designs in a variety of dynamic applications. The available simulation software will additionally provide a pathway for a more basic understanding of the influence of parameter settings, system configuration changes and changes in the control software.

6. Summary

The experimental implementation of an initial fuel cell HiL capability has been undertaken at the Hawaii Fuel Cell Test Facility of the Hawaii Natural Energy Institute at the University of Hawaii. This paper presents an overview of the fuel cell HiL concept and the design and experimental configuration of this dynamic fuel cell test system, which is designated as HiL #1. The implementation of HiL #1 has been discussed in terms of the basic fuel cell HiL methodology, the experimental configuration, and the initial experimental results obtained.

The objective was to demonstrate the first step towards a Fuel Cell HiL methodology that can be used to evaluate the dynamic behavior of fuel cells and of fuel cell system designs and control strategies in any dynamic fuel cell system application for which a proper causal dynamic simulation tool is available. This application simulation tool must provide strict separation of control and component simulation. In this paper, the adaptation of an existing FCV simulation tool as an example of a dynamic application has been discussed and demonstrated, and initial experimental results for this example are reported.

The generation of real-time simulation set-points by *FCVSim* in this initial testing is performing properly and the dynamic fuel cell test system is translating these set-points into actual physical anode and cathode flows to the fuel cell test object. However, there is evidence of “hunting” on the part of the anode and cathode flow controls and of delays, as well as undershoot and

overshoot, between the set-points and the actual data responses. Further testing and analysis has determined that these artifacts are due to both software and controller limitations in the Test System Controller provided by the dynamic test system vendor. Eliminating these artifacts through in-house software and hardware modification is now underway as the next step in the development process for the fuel cell HiL methodology.

The fuel cell HiL concept and methodology discussed in this paper can support the analysis of fuel cell technologies and fuel cell system designs for any application (and can test solutions for control strategies) prior to the need for a major investment in complete system hardware and full scale testing programs (e.g., for FCVs testing via dynamometer). The only *a priori* requirement is that a dynamic simulation tool for the application must exist (preferably in Simulink) along with appropriate dynamic use patterns.

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