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Fuel cell hybrid drive train test facility

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Abstract

Fuel cells are expected to play an important role in the near future as prime energy source on board of road-going vehicles. In order to be able to test all important functional aspects of a fuel cell hybrid drive train, the Automotive Institute of the HAN University has decided to realize a stationary test facility, comprising an 8 kW PEM stack and a 185 [Ah] 48 [V] NiCd battery, which is connected to an asynchronous motor, which is loaded by an eddy current brake. The objective of the test facility is to provide an efficient and accessible test platform for the development of fuel cell hybrid drive trains and subsystems. This paper describes the HAN fuel cell hybrid drive train test facility and some of the experimental results that have been obtained during the process that was needed to make the facility operational.

Keywords: PEM fuel cell, test facility, control system, demonstration, education

1 Introduction

Automotive engineers are facing a major change in technology for the vehicle drive train. Series produced hybrid electric vehicles are seen in increasing numbers on the roads and this trend is expected to continue during the coming years. Alternative fuels, among which also Hydrogen, are studied extensively all over the world in order to assess their viability as a fuel for automotive application. This leads educators in the automotive power train field to incorporate these technologies in their curriculum, so that the future automotive engineer is well prepared to face new power train design challenges, like power electronics and electric power components, like generators, motors, super capacitors, batteries, fuel cell stack systems, energy management of complex (hybrid) electric drive trains, codes, standards and safety issues related to the use of hydrogen and high DC voltages. The HAN University of applied sciences, having a large automotive department (~1000 students), has decided to put focus on the application of hydrogen in vehicles, both in the internal combustion engine and by using fuel cells. In 2007 the University opened their first hydrogen test facility.

This paper describes the HAN fuel cell hybrid drive train test facility and some of the experimental results that have been obtained. The objective of the test facility is to provide an efficient and accessible test platform for the development of fuel cell hybrid drive trains and subsystems. Since all components of the balance of plant are fully accessible, effects of modifications of these components may be studied in situ [1]. The facility is also ideally suited for the study of energy management strategies.

2 Hardware description

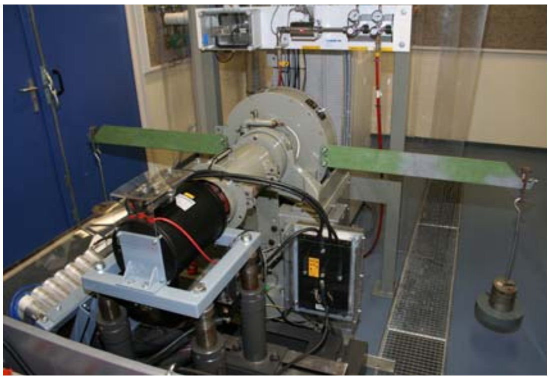

Figure 1. Impression of the Fuel cell hybrid drive train test facility, showing the drive motor, motor inverter and eddy current brake with torque sensor calibration arms attached. In the background, the cabinet with fuel cell stack can be seen.

The HAN hybrid drive train test facility has been realized in order to be able to test complete drive trains in a stationary setup. This facilitates not only ease of operation and accessibility, but also guarantees a safe environment and a setup that is accessible for educational purposes. However, some aspects cannot be tested in this facility, like the effect of vehicle vibrations. Figure 2 shows a schematic overview over the test facility, shown in Figure 1. The fuel cell system comprises a 68 cell 8 kW peak power PEM stack supplied by Nedstack bv. and all balance of plant components like humidifiers, air compressor, hydrogen supply and recirculation pump, cooling system and various valves and sensors for temperatures, flows, pressures, voltages and currents. This system is electrically linked to a DC-DC converter, feeding a 48 Volt DC bus. A NiCd battery of 48 [V] with a capacity of 185 [Ah] and a motor inverter are also connected to this bus. Additionally, the bus can be loaded with an electronic load, simulating additional power consumers like an air conditioning unit. The inverter is connected to an asynchronous 8kW motor with a maximum torque of 80 Nm and maximum speed of 4000 rpm. The motor is mechanically linked to an eddy current brake which is used to simulate road load losses. This brake is also used to simulate vehicle inertia. The facility is ideally suited to test drive train behaviour over driving cycles, similar to those presented in [2]. As indicated in Figure 2, several controllers are needed to stabilize operation of the entire system and to bring the system in its most optimal operating point with fastest possible settling time. For the fuel cell stack, the compressor speed and cooling water temperature must be controlled, depending on the stack load. By means of the DC-DC converter, the amount of battery charging power can be controlled. The inverter is used for control of the motor speed and the eddy current brake requires a separate controller for the road load torque. Figure 3 shows the physical layout of the test rig, including all power measurement positions.

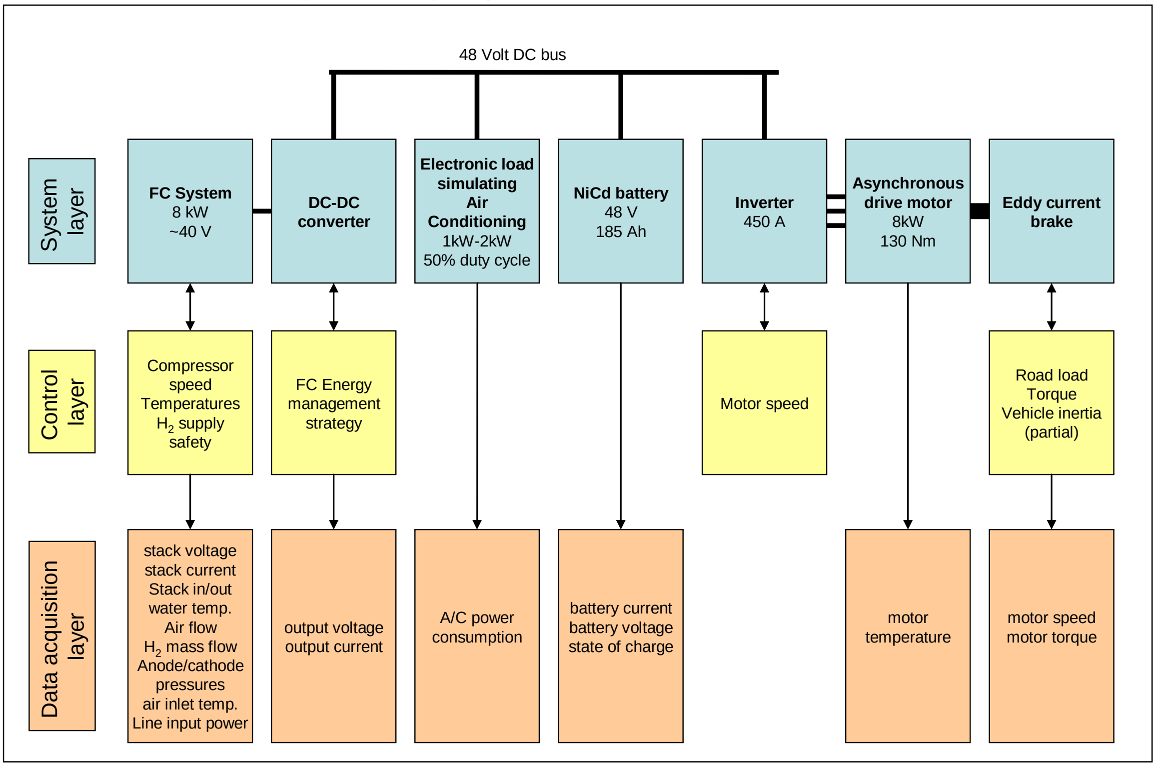

Figure 2. Schematic overview of the HAN fuel cell hybrid drive train test facility.

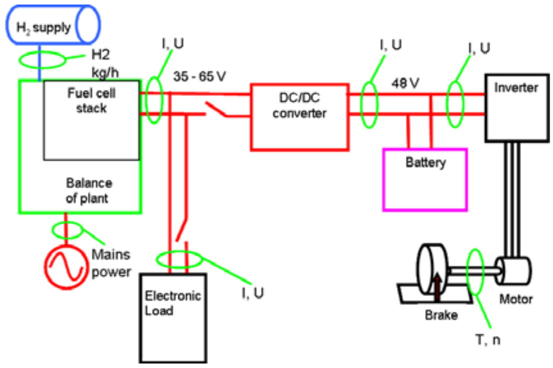

Figure 3. Physical test rig layout, showing power flow measurement points.

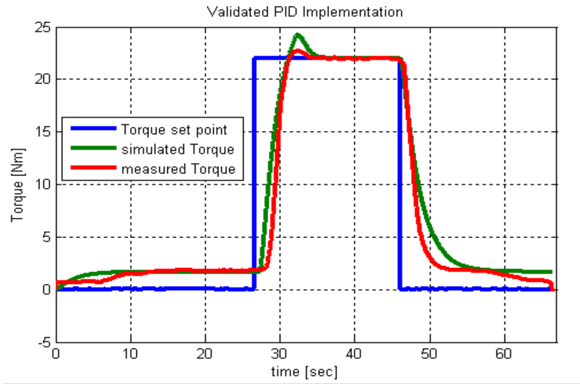

Figure 5. Closed loop response at 800 [rpm] motor speed.

3 Example 1. Low level control

In order to simulate a vehicle propulsion system on the test rig, the motor inverter should follow a speed setpoint and the eddy current brake must realize a torque setpoint. For this purpose, two control loops and a vehicle simulator are implemented.

For the design of the torque controller, a second order model is derived for the eddy current brake, on the basis of step response data as shown in **Error! Reference source not found.**.

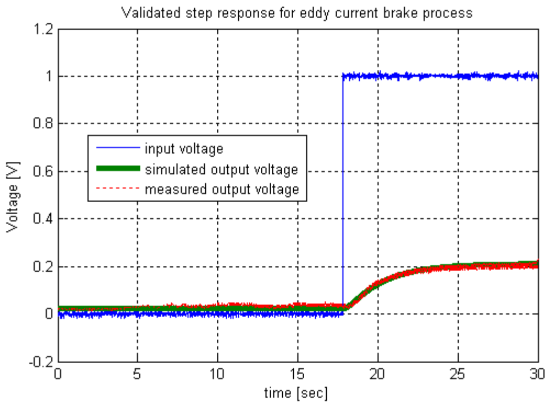

Figure 4. Open loop step response of eddy current brake

On the basis of this model, a PID controller is designed using the root-locus method. Due to its design, an eddy current brake is not capable of generating torque at low speeds. In order to avoid integrator wind-up, a special measure is implemented that reduces the brake torque setpoint to zero at zero speed.

Figure 5 shows the resulting closed loop response of this controller. The limitations in the dynamic response of the eddy current brake lead to the rather long rise time as can be seen in Figure 5.

Also the motor inverter combination is modelled. As the response of the motor inverter combination appears linear over the complete control range, one controller design is sufficient.

The steady state error, resulting from the slip in the asynchronous motor when loaded, is compensated by using a PI controller. The resulting closed loop speed response of a step up and step down in both speed (0 to 2,700 rpm) and torque (0 to 15 Nm) is shown in Figure 6.

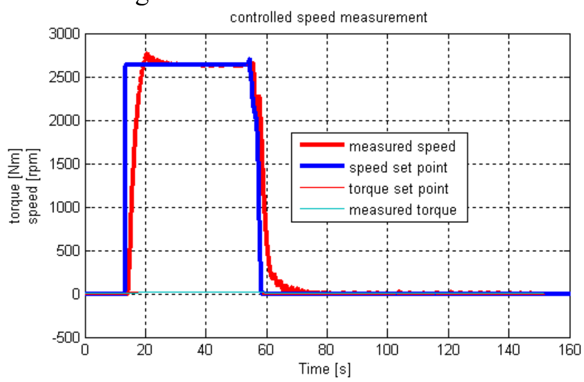

Figure 6. Closed loop step response of the speed control loop at a torque of 15 Nm

A general vehicle model is implemented in the software. This model can be tuned in terms of vehicle parameters (vehicle mass, rotating inertial mass, frontal area, rolling resistance, air resistance, etc.) and propulsion line parameters (efficiencies, energy management strategy, etc.). Based on a driving cycle, the vehicle model provides setpoints over time for speed and torque. The low level controllers discussed, realize the speed and torque trajectories on the test rig.

4 Example 2. System identification and control

The experimental set-up is fully equipped for system identification and control applications. Many variables are measured and components like sensors or actuators are added or replaced easily. Also the lack of commercial pressure of production makes various time consuming measurements possible.

4.1 Problem Definition

If a fuel cell system is used in a vehicle then the control requirements are expressed as:

- The fuel cell system must be stable at all times.
- The electric power demand should be met.
- The fuel cell system must be operated as efficiently as possible.
- Operation of the stack must not affect the durability of the fuel cell stack.

To achieve these goals robust and optimal control is applied. The processes inside the fuel cell stack are non-linear and dynamics vary under different circumstances. A robust controller copes with these uncertainties. However, also an optimization problem must be solved. The power generated by the fuel cell must be used as efficiently as possible. Power required to operate the fuel cell system should be minimized. Regardless to this matter, the power that is requested must be delivered as soon is possible. Various inputs and outputs influence the behaviour of the fuel cell stack. Therefore a MIMO controller design method is applied.

4.2 Method

To design a robust and optimal controller an accurate model is required. Because many variables influence or disturb the process, the augmented plant is used as definition of the control problem [3]. The augmented plant relates exogenous inputs w disturbing the control loop to the exogenous outputs z defining the variables important for control. Also the measureable outputs v available for control and the control inputs u are defined.

Figure 7 presents the augmented plant, including shaping and weighting filters, for the two degree of freedom problem with feedforward and feedback, used for fuel cell system controller design. In order to design a well functioning controller, all system parameters must be analyzed. From that analysis is seen that two specific parameters have great influence; stack temperature and the amount of oxygen inside the stack. Both parameters are well controllable and can therefore be used to reach the control goals.

The amount of oxygen inside the stack defines the generated amount of power, assuming the hydrogen flow to be constant. The amount of oxygen inside the stack depends on the air mass flow generated by the compressor. This compressor is also the largest consumer of electrical power inside the fuel cell system. The electric power consumed by the compressor depends on the amount of air mass flow. Reducing the air mass flow increases the efficiency of the total system.

The temperature of the stack influences the chemical reaction inside the membrane. A too high temperature will cause the stack to dry out. If the temperature is too low, the stack drowns. Especially, if the amount of oxygen is limited to the amount necessary for the demanded power, the stack temperature becomes critical. Additional heat is generated by internal losses. The amount of heat

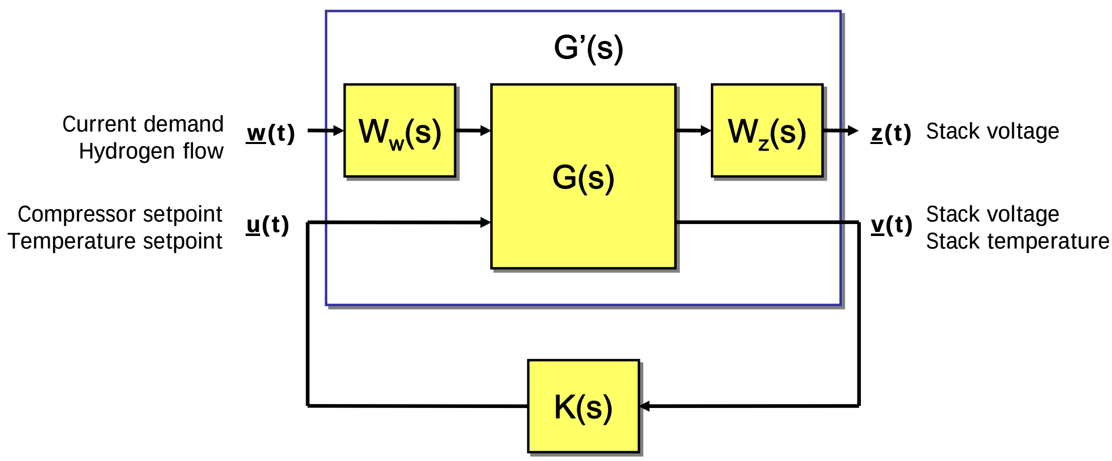

Figure 7. The augmented plant

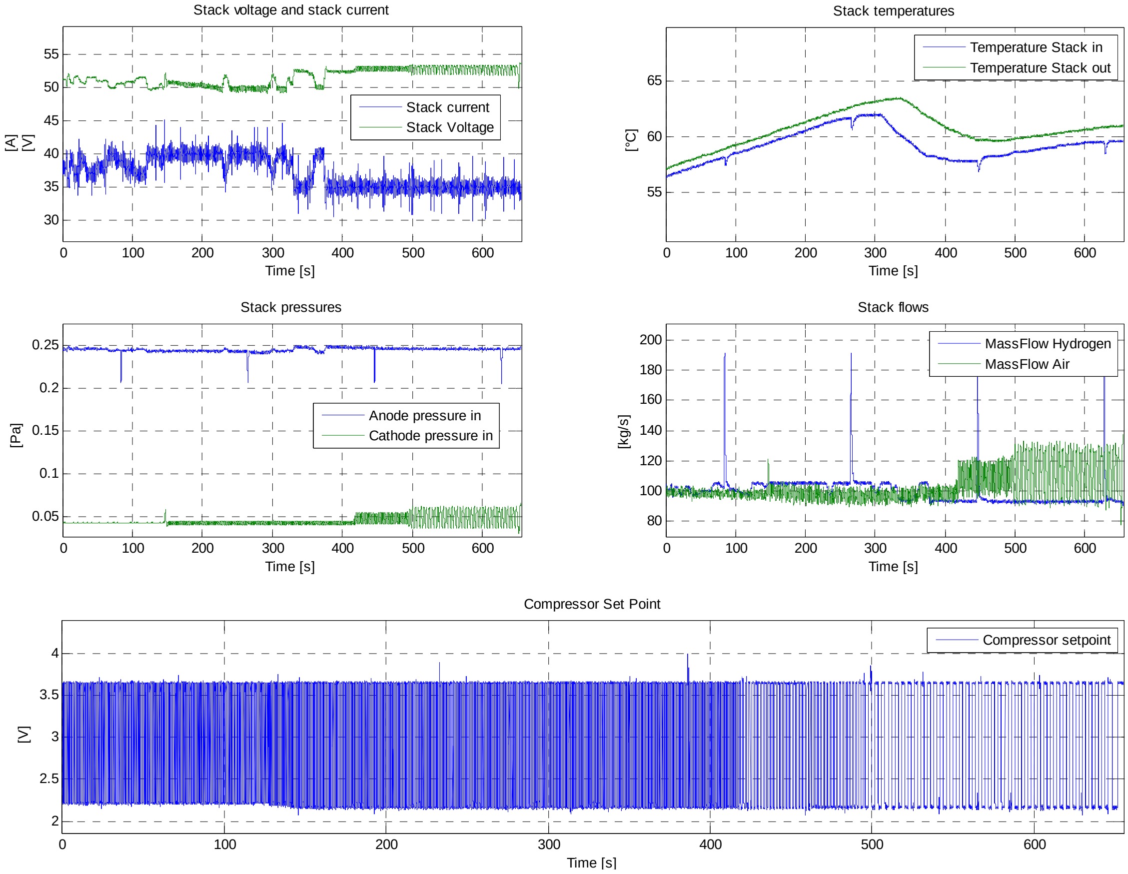

Figure 8. Example of experimental results of a model estimation.

generated is directly related to the amount of reactions, which is directly related to the amount of generated power. The cooling system must keep the temperature constant. This local temperature controller is assumed to be well tuned. The system controller will generate an optimal temperature set point.

For the situation described, the exogenous inputs are defined as:

- Hydrogen flow, depending on the amount of reactions in the membrane.
- Current demand, which represents a large disturbance which cannot be influenced.

The control inputs are defined as:

- Setpoint to the local compressor speed controller, changes airflow on the cathode, the amount of hydrogen stays constant. The compressor is one of the largest consumers thus to produce current as efficient as possible, the compressor set point should be minimized.
- Set point to the stack temperature controller.

The exogenous outputs are defined as:

- Stack voltage which, together with the stack current, defines the delivered power.

The outputs available for control are defined as:

- Stack voltage, the controller should maintain the stack voltage.
- Stack temperature, the stack temperature should be within safe regions but should also be kept at an optimal value for the delivered power level.

4.3 Process identification

This model mentioned in section 4.2 was identified using measurements. To collect as much information as possible from the system, the controllable inputs where changed constantly and independently. The air mass flow was influenced by applying an actuating signal on the compressor with varying amplitude and frequency. Also the cooling water inlet temperature was changed as well by applying as small steps on the current.

Typical results of these measurements are presented in Figure 8.
Using system identification methods, linear as well as non-linear models were estimated. Although the fuel cell process is non-linear, for a large operating range the system may be assumed linear. For controller design the model was reduced to a third order state space model. This reduced model was used to calculate an H∞ controller using algorithms proposed by Skogestad and Postlethwaite [3].

4.4 Results

For validation, the estimated model was simulated with new measured inputs. Next, through simulation the performance and robustness of the H∞ controller designed was analyzed. Figure 10 presents the simulated results with the new robust controller, compared with the measured results of the original controller.

4.5 Discussion

Figure 10 shows that during the first 100 seconds, the controller operates outside the defined linear operating area. Next, the stack current is around the point of operation. Clearly is seen that the compressor is operated at a lower power consumption than in the original PLC-based system for t > 120 [sec]. Because of this lower compressor power, the system efficiency of the total system is increased.

5 Example 3 System efficiency determination

The test facility is well suited for the determination of the efficiency of subsystems, like the fuel cell stack, the air compressor, the electric motor or the DC-DC converter. A clear insight into the efficiency of the various subsystems allows for a

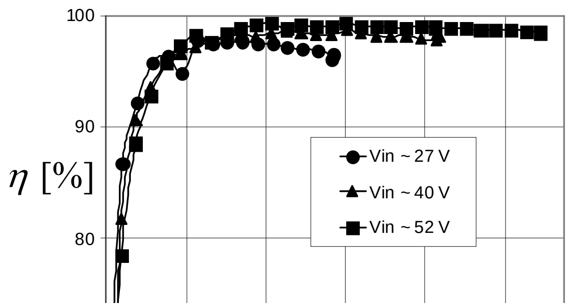

Figure 9. Typical efficiency vs. output power data for the DC-DC converter at different input voltage levels. Output voltage: 75 [V].

more accurate energy management of the entire system [4]. Experiments have been carried out to determine the efficiency of the DC-DC converter in steady state operation. The input power to the converter was drawn from a large set of lead acid batteries, whereas the output power was regulated by means of an electronic load of type TDI WCL 488. Typical results are shown in Figure 9.
Even at low input voltages, the efficiency of the converter proved to be higher than 95% at loads higher than 1 kW. This data will be incorporated in the full vehicle quasi static simulation model that is under development. A separate paper reports on its development status [5].

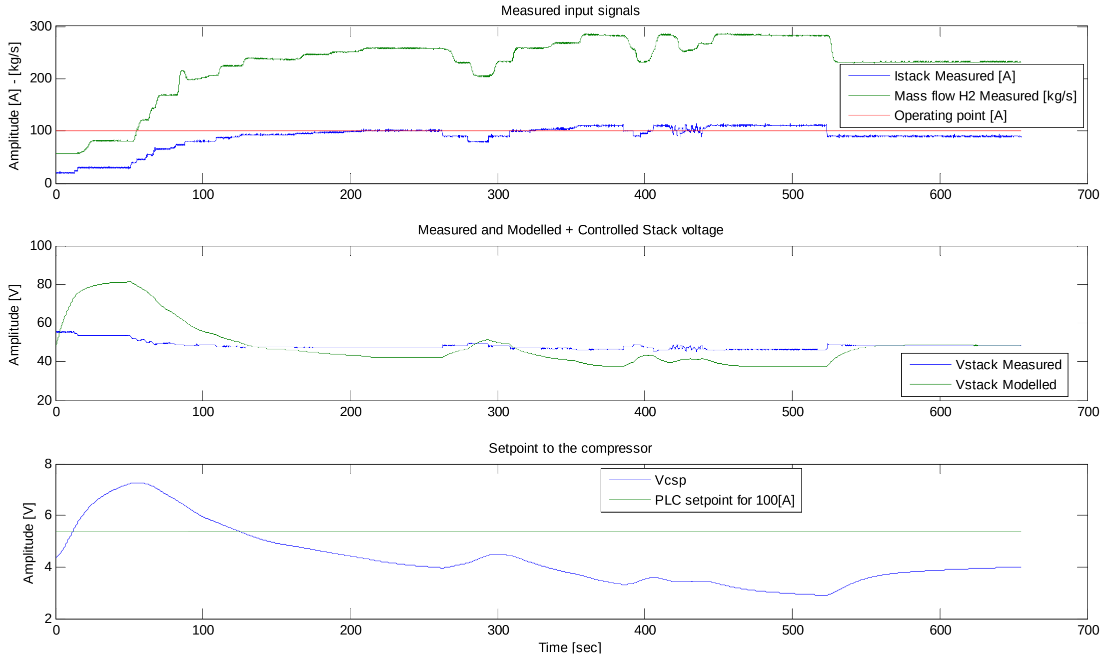

Figure 10. Controlled Stack Voltage and Compressor Set point.

Acknowledgments

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