Asia Pacific Research Initiative for Sustainable Energy Systems 2011 (APRISES11)

Office of Naval Research
Grant Award Number N0014-12-1-0496

Hydrogen Energy System Simulation Model for Grid Management Applications

Task 3.5

Prepared For

Hawaii Natural Energy Institute

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Hydrogen Renewable Energy System Analysis

June 2017

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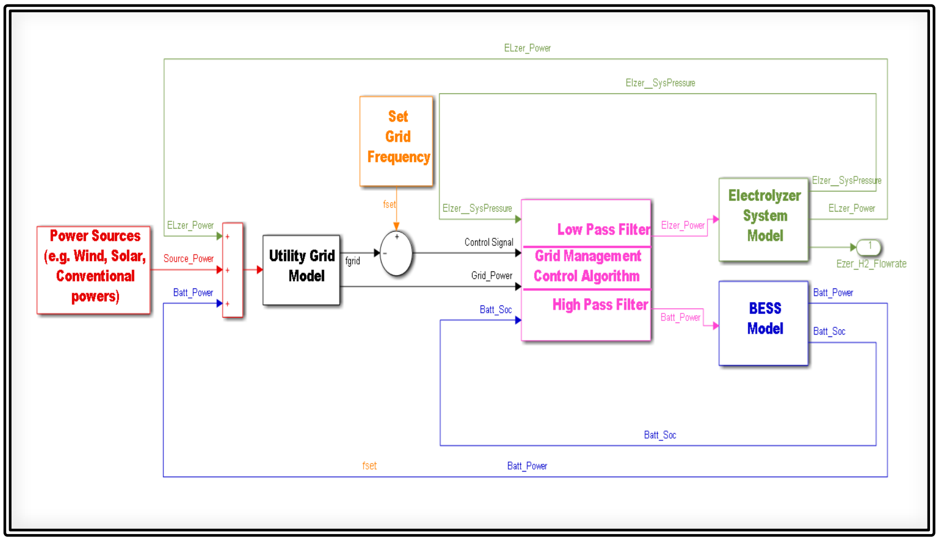

Progress Report

Document prepared for HNEI
by
Dr. Mebs Virji

30th June 2017

Hydrogen Energy System Simulation Model for Grid Management Applications
Progress Report
30 June 2017

This report documents the progress in developing a dynamic simulation model for conducting analysis of the HNEI Hydrogen Energy System that is being evaluated as a potential tool to support the use of an electrolyzer to provide ancillary services to the grid.

Objectives

The main objectives of the Hydrogen Energy System (HES) Simulation Model:

- Develop electrolyzer, battery energy storage system (BESS), renewable power sources and utility grid models using measured performance data of a hydrogen energy system deployed on the Island of Hawaii;
- Develop, evaluate and optimize a grid management control algorithm under a wide range of grid operating conditions;
- Characterize the performance of an HES system under realistic dynamic or cyclic load profiles;
- Study the trade-offs between different sizes of electrolyzer systems (kW to MW) and storage systems required for optimal grid management strategies incorporating different renewable power sources; and
- Evaluate the performance of a hybrid electrolyzer system (electrolyzer + BESS) using different grid management control algorithms.

Grid Management HES Simulation:

- The HES simulation is being developed in the Matlab and Simulink Environment;
- The HES simulation will have an HES model that will include the following:
  - Electrolyzer system model;
  - Grid power system model;
  - BESS model;
  - Control algorithms model; and
  - Different renewable power source models.
- HES simulation will be used to evaluate the hybrid electrolyzer-BESS system under different grid management control algorithms as functions of frequency deviations.

Hydrogen Energy System Model

Electrolyzer Model

A PEM electrolyzer model has been developed to determine the cell voltage of an electrolyzer cell as a function of supply current and other operating parameters such as temperature, pressure and water flow rate. Using this model, a performance characteristic (V-I curve) of the electrolyzer can be determined and can be used to calculate the electrical power required by the electrolyzer for the production of hydrogen at different currents or current densities. The required cell voltage of a PEM electrolyzer can be estimated by the following equation:

$$V_{cell} = V_o + \eta_{act,\,a} + \eta_{act,\,c} + \eta_{ohmic} + \eta_{con}$$

Where,

$\mathbf{V}_o$ is the equilibrium voltage;

$\eta_{act,\,a}$ and $\eta_{act,\,c}$ are activation over-potentials at anode and cathode, respectively;

η_{ohmic} is the ohmic over-potential across the proton exchange membrane; and

η_{con} is the concentration over-potential due to bubbling of exiting oxygen which could limit the permeation of water to the anode especially at high current densities.

This equation calculates the cell voltage as a function of many operating parameters of the electrolyzer cell, anode and cathode electrodes and membrane properties. Some of the main parameters which are employed in the model to predict the performance of the PEM electrolyzer are:

a. Current, Pressure and Temperature;
b. Anode and cathode exchange current density;
c. Membrane thickness and hydration; and
d. Limiting current density.

The electrolyzer cell model was implemented in the Matlab/Simulink environment to study the effect of varying these parameters on the cell voltage of the PEM electrolyzer. The Proton C30 electrolyzer operating conditions were used in the model and model results were compared and validated using measured performance data from the Proton C30 electrolyzer. However, more specific measurement will be needed, especially at lower currents, to fully validate the model so as to predict accurately the performance of the Proton C30 electrolyzer.

Results from the PEM Electrolyzer Model:

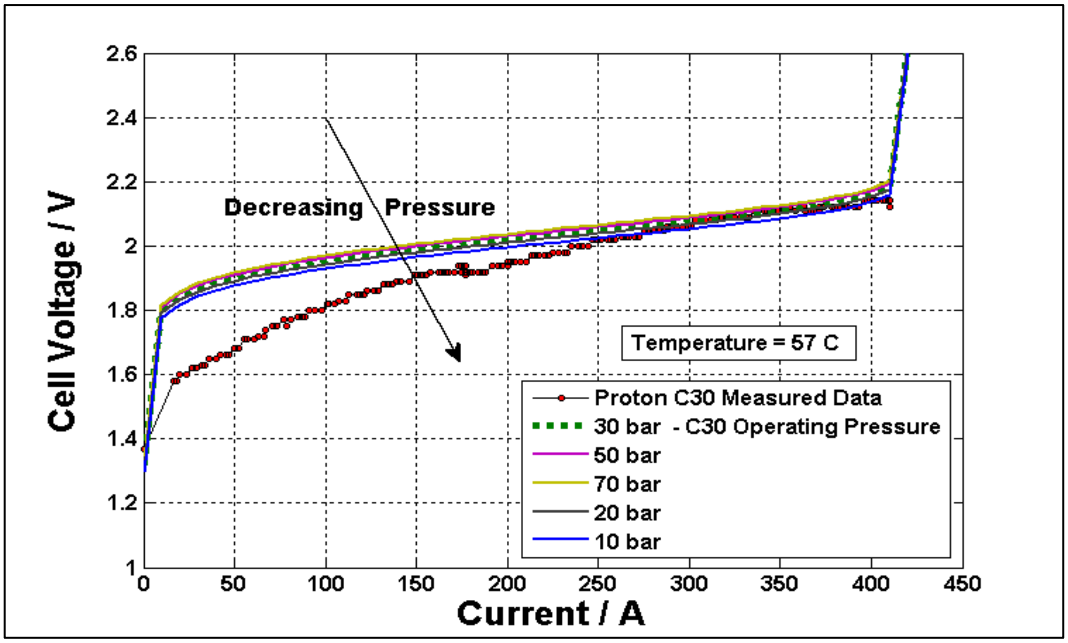

Figure 1: Electrolyzer Pressure

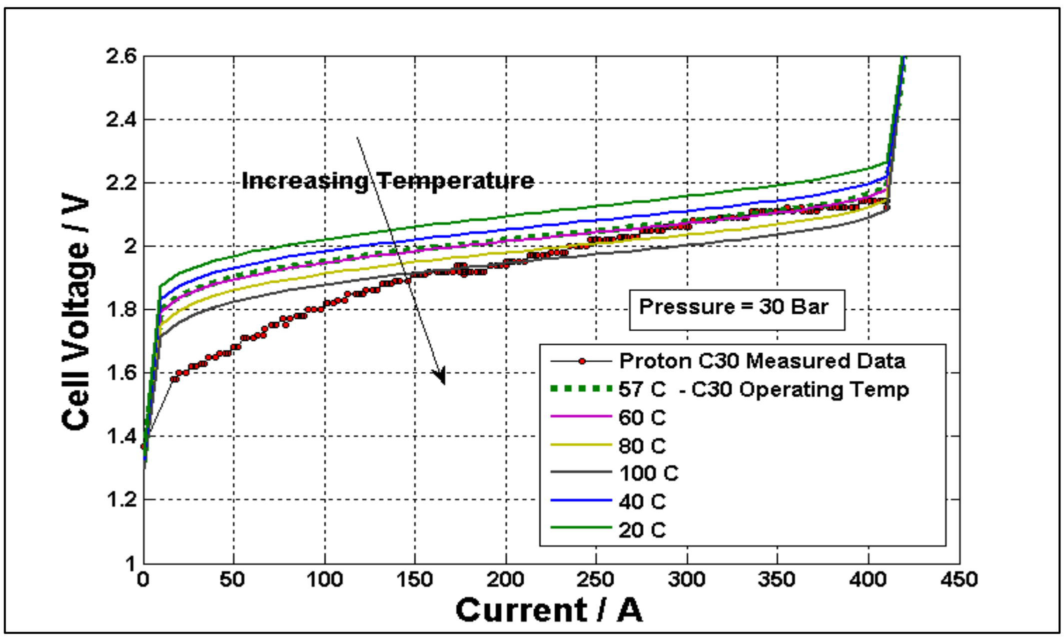

Figure 2: Electrolyzer Temperature

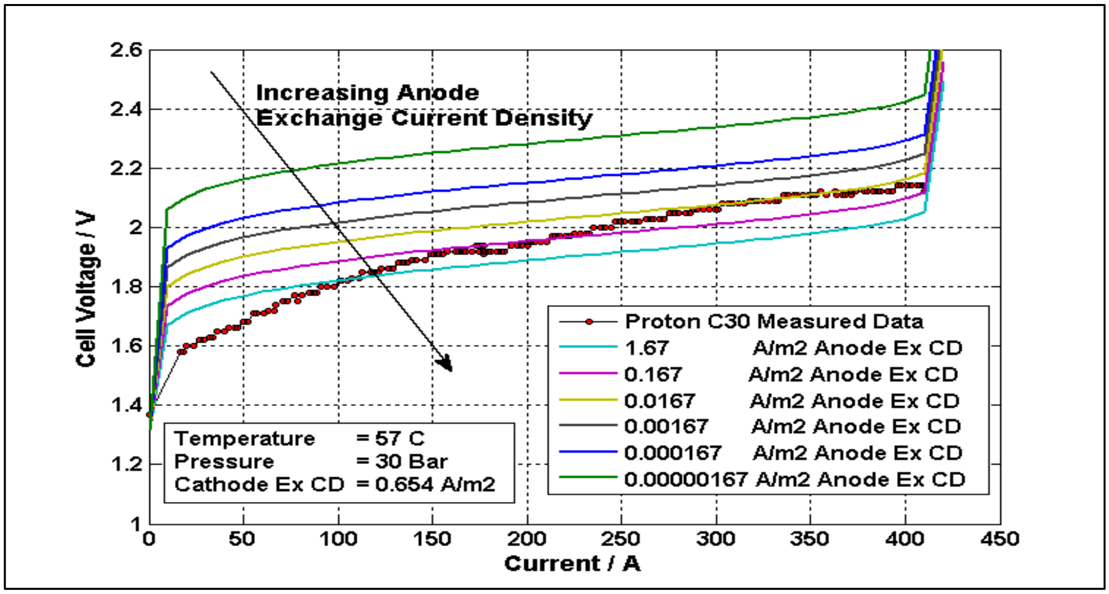

Figure 3: Anode Exchange Current Density

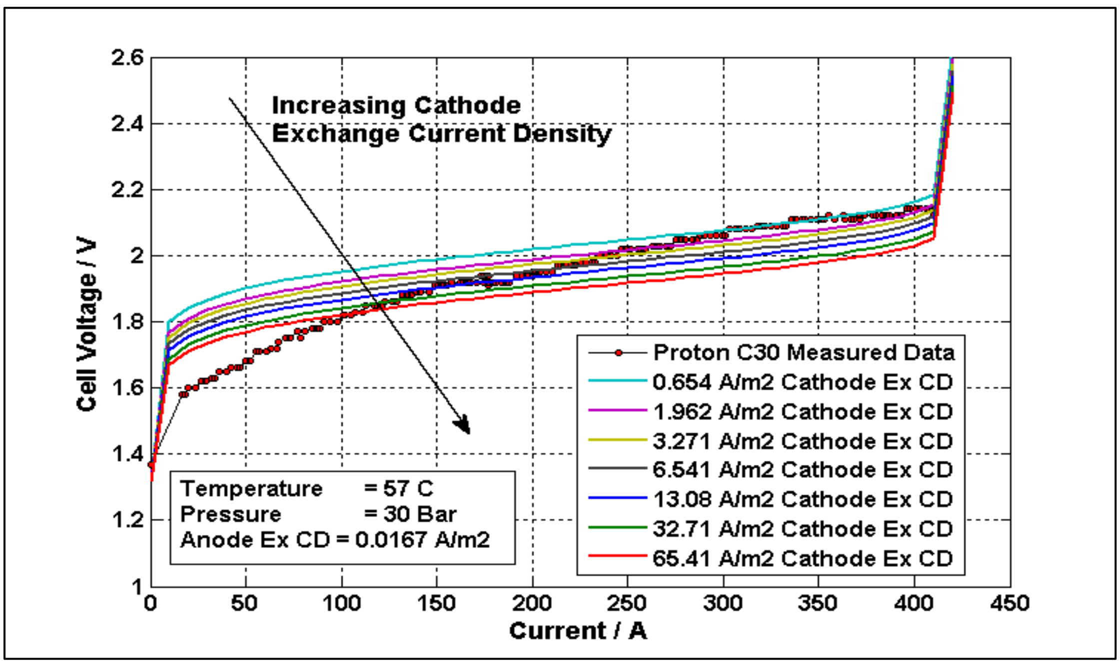

Figure 4: Cathode Exchange Current Density

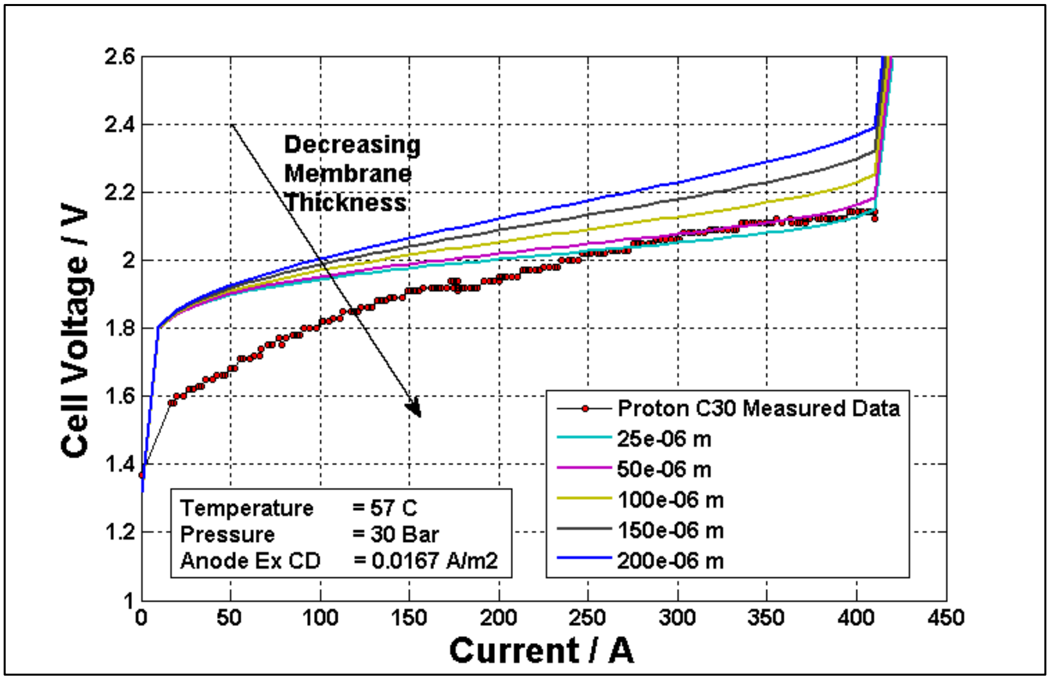

Figure 5: Membrane Thickness Variation

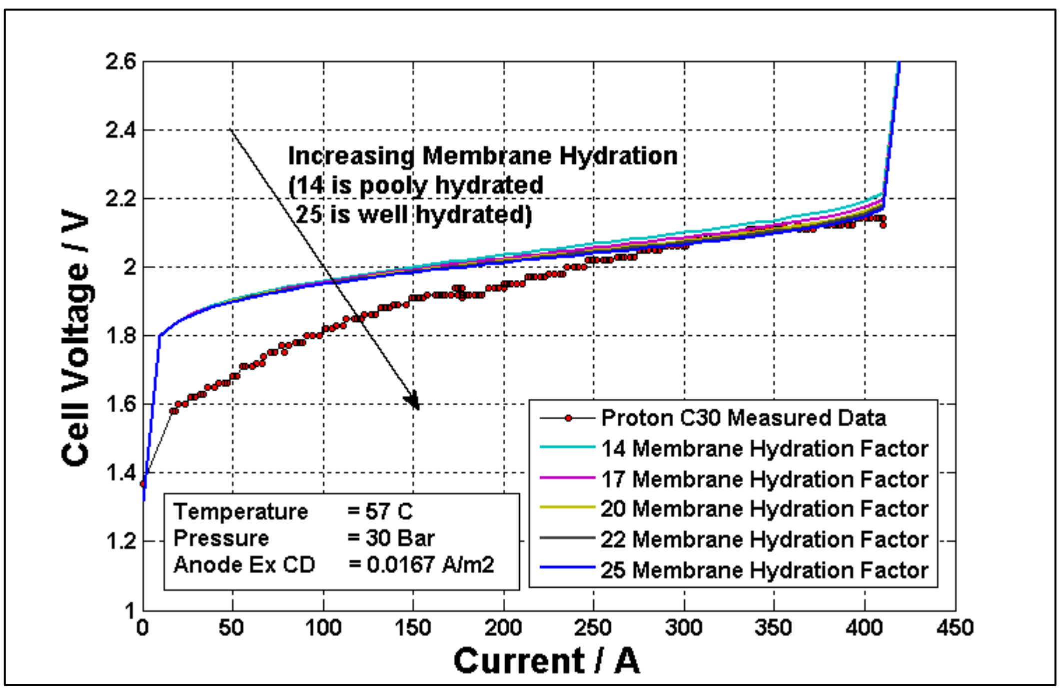

Figure 6: Membrane Hydration Variation

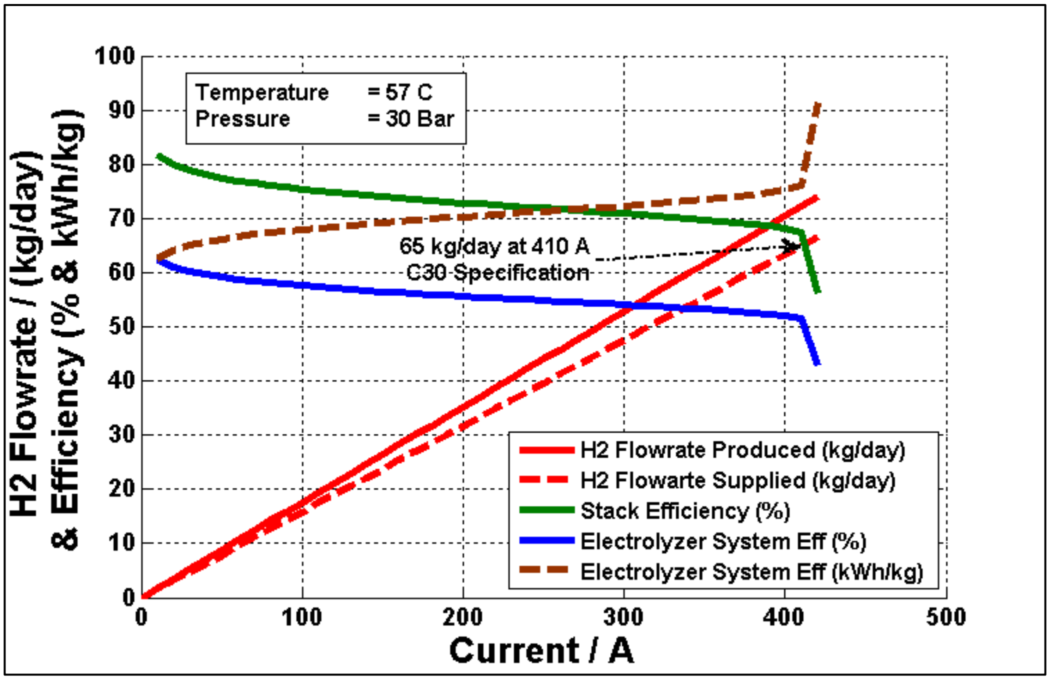

Figure 7: H_2 Flow Rate & Efficiencies of C30 System

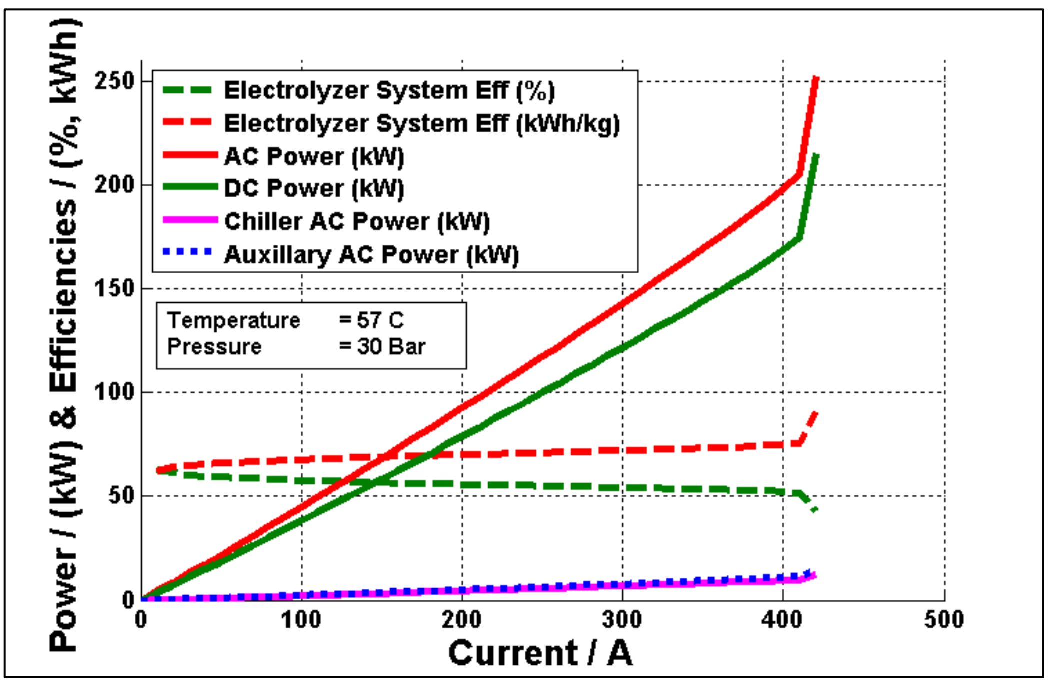

Figure 8: AC & DC Power of C30 System

Electrolyzer System Model in Simulink

The electrolyzer system was designed and developed in the Matlab/Simulink environment and it contains model blocks for current control, thermal control, electrolyzer cell and stack model, cathode model for ramping the system pressure and buffer tank model for ramping the product pressure. Figure 9 shows the overall electrolyzer system as implemented in the Matlab/Simulink environment.

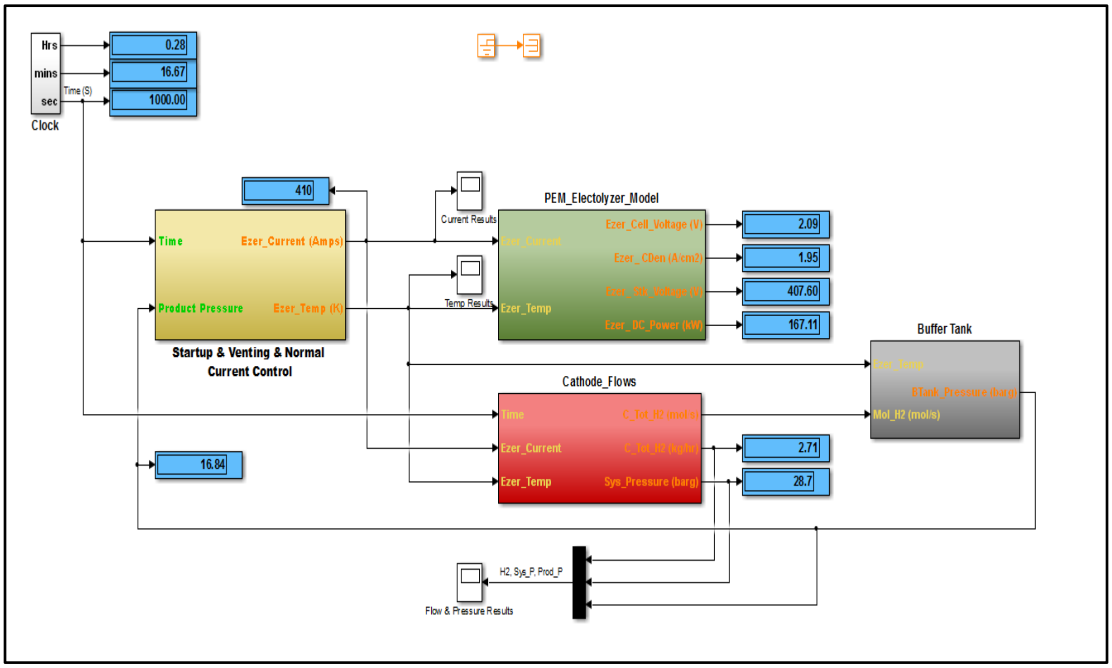

Figure 9: Electrolyzer System Model in the Matlab/Simulink Environment

The thermal, current, hydrogen flow-rate and pressure controls and time constants were designed and tuned to simulate the dynamic ramping characteristics of the Proton C30 electrolyzer during the startup (powering up) process, safety check and venting process, and normal operational process. Figures 10 to 14 show the following:

Figure 10:	Block for the electrolyzer cell and stack model.
Figure 11:	Block for current and thermal control model for the startup, venting and normal operations + current control during the normal operations.
Figure 12:	Block for the overall system pressure model for the startup, venting and normal operations.
Figure 13:	Block for the system pressure control model during the normal operation.
Figure 14:	Block for the buffer tank pressure control model.

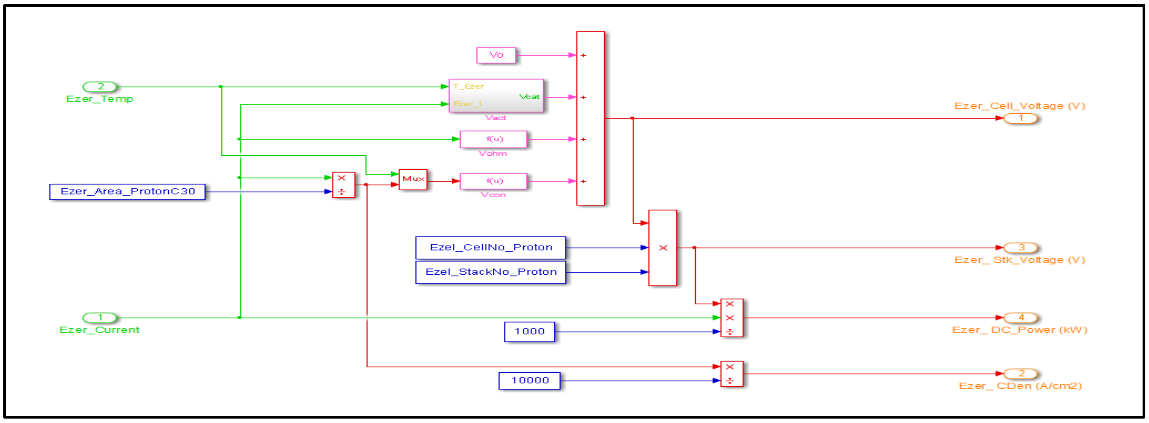

Figure 10: Electrolyzer cell and stack model block

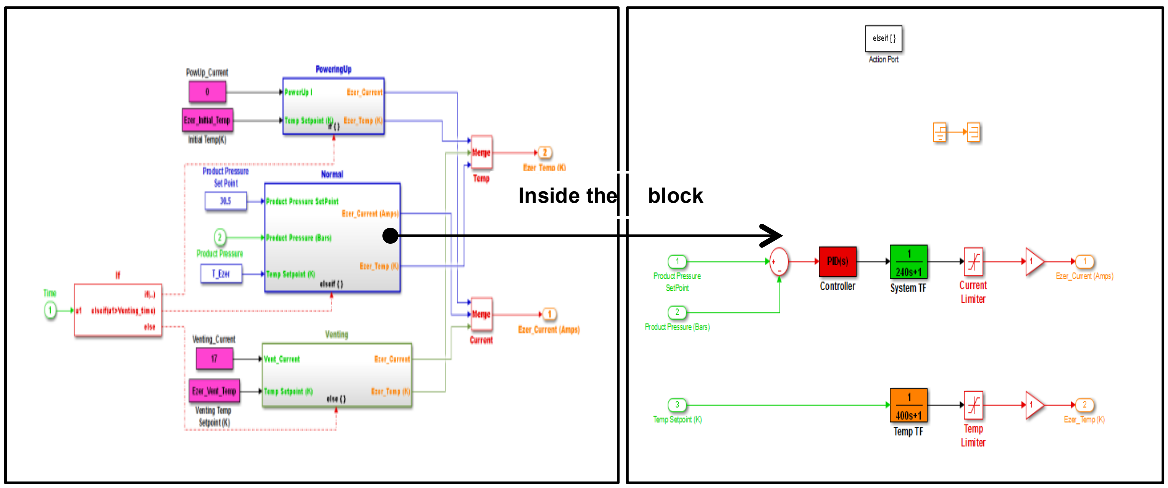

Figure 11: Current and thermal control model block

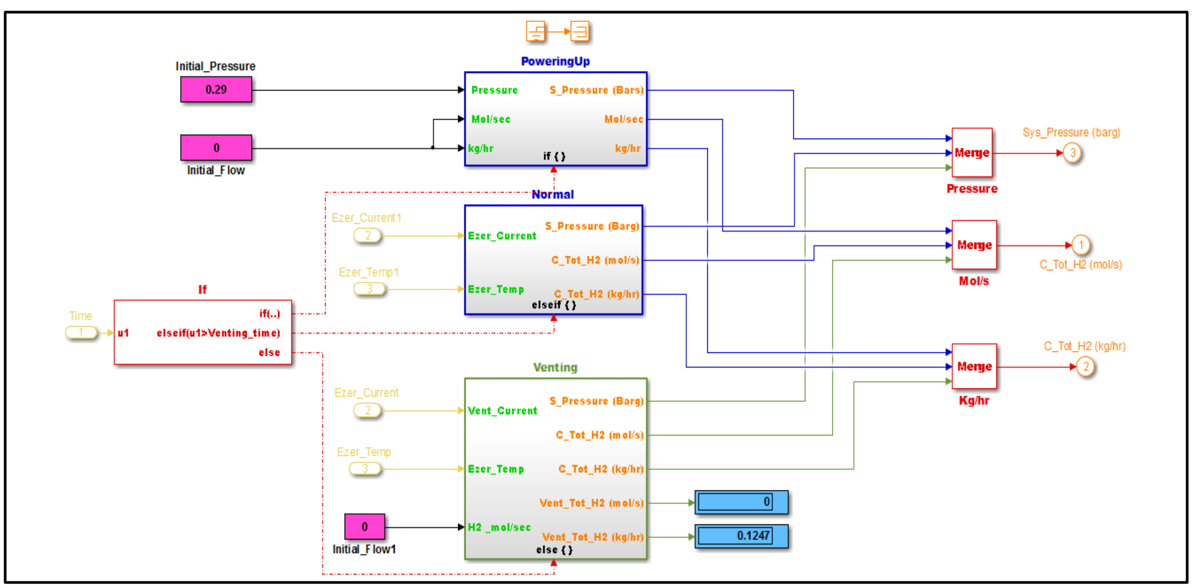

Figure 12: Overall system pressure control model

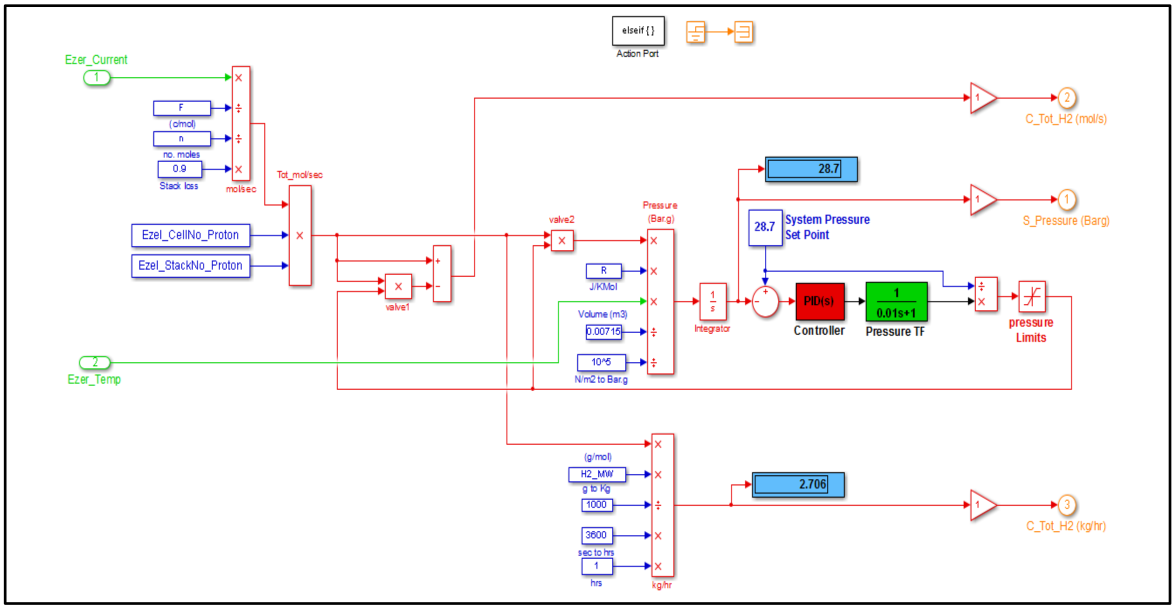

Figure 13: System pressure control model block during the normal operation

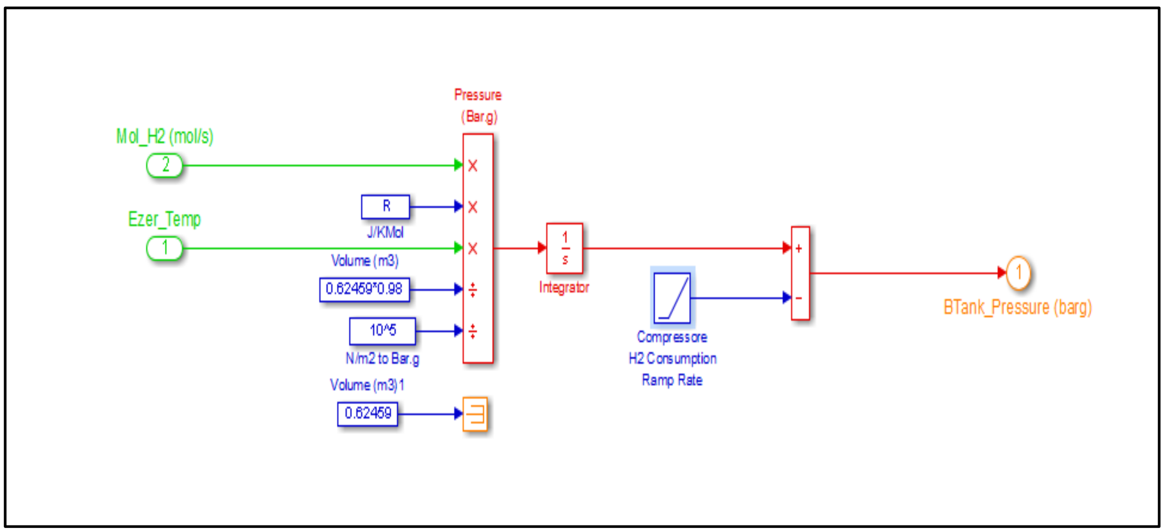

Figure 14: Buffer tank pressure control model block

Results from the PEM Electrolyzer System Model:

The electrolyzer system simulation was run to generate current, system and product pressures, hydrogen flow rate and temperature characteristic profiles for the startup, venting and normal operational processes of the system. These results profiles were then compared to the measured data from the Proton C30 electrolyzer system. Figure 15 shows the simulations results compared to the data from the Proton C30 electrolyzer system for the H_2 Flow Rate, System Pressure, Product Pressure and stack current while Figure 16 shows the simulated temperature results compared with measured data from the electrolyzer system. The results show that the control parameters and the time constants are very well tuned to accurately estimate the operational characteristics of the actual Proton C30 electrolyzer system operations.

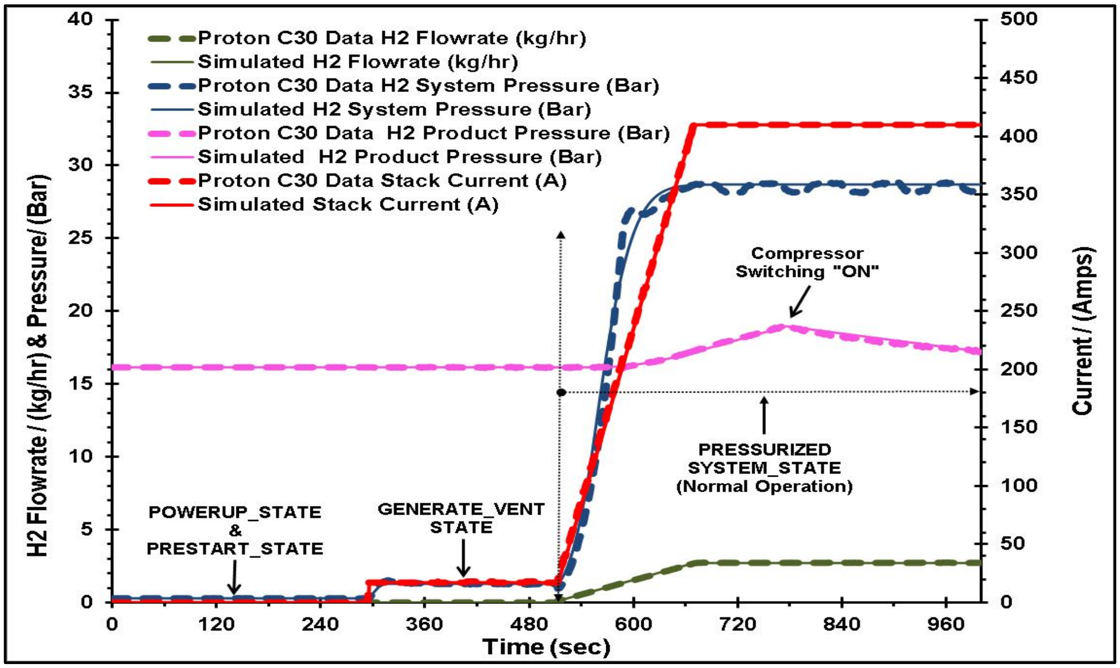

Figure 15: Simulated results compared with data from the Proton C30 Electrolyzer

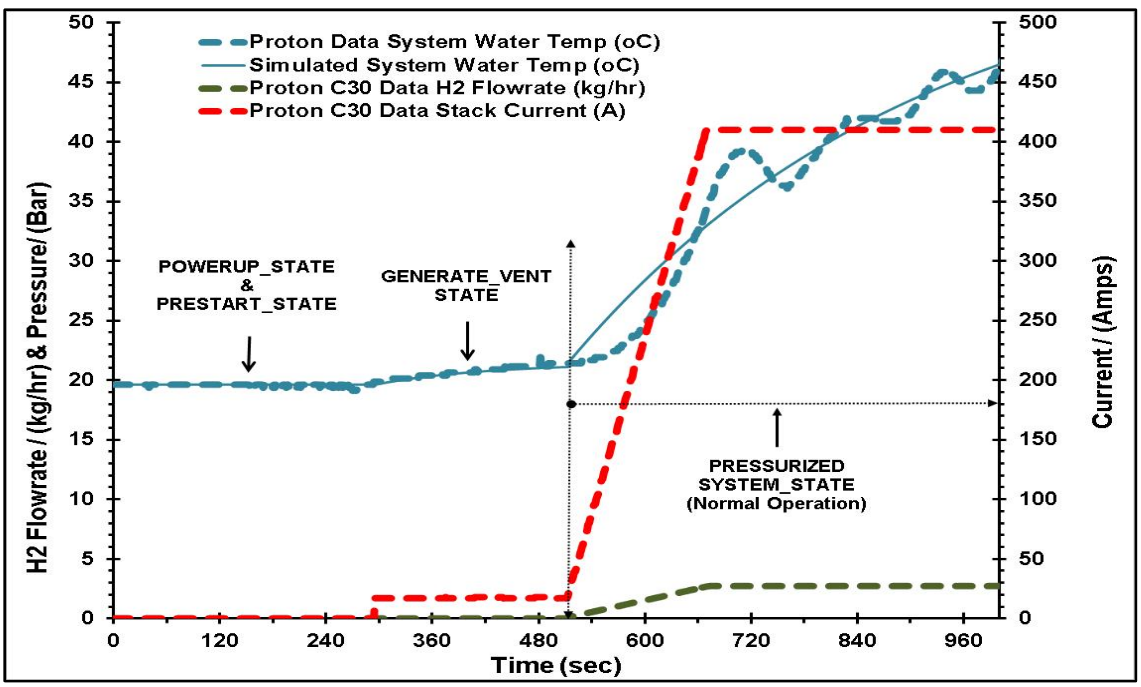

Figure 16: Simulated temperature result compared with data from the Proton C30 Electrolyzer

450 bar Compressor Cycle Model:

The hydrogen compressor ramp rate model was updated in the buffer tank pressure model to include the cycle for filling up the buffer tank with hydrogen and subsequent compression of the hydrogen to 450 bar by the compressor. A pulse generator was used to initiate the starting and stopping of the compressor as programed in the PLC of the actual Hydrogen Energy System installed at NELHA on the Big Island. The buffer tank takes about 13 minutes to fill to about 30 bar by hydrogen from the electrolyzer while the compressor takes about 20 minutes to compress the hydrogen to 450 bar into the tube trailer tanks. The model was validated using measured data from the Proton C30 electrolyzer. Figure 17 shows the implementation of the compressor cycle model into the buffer tank model of the HES Simulink overall model. Figure 18 shows the results from the model which are compared to the measured data from the C30 Electrolyzer system database.

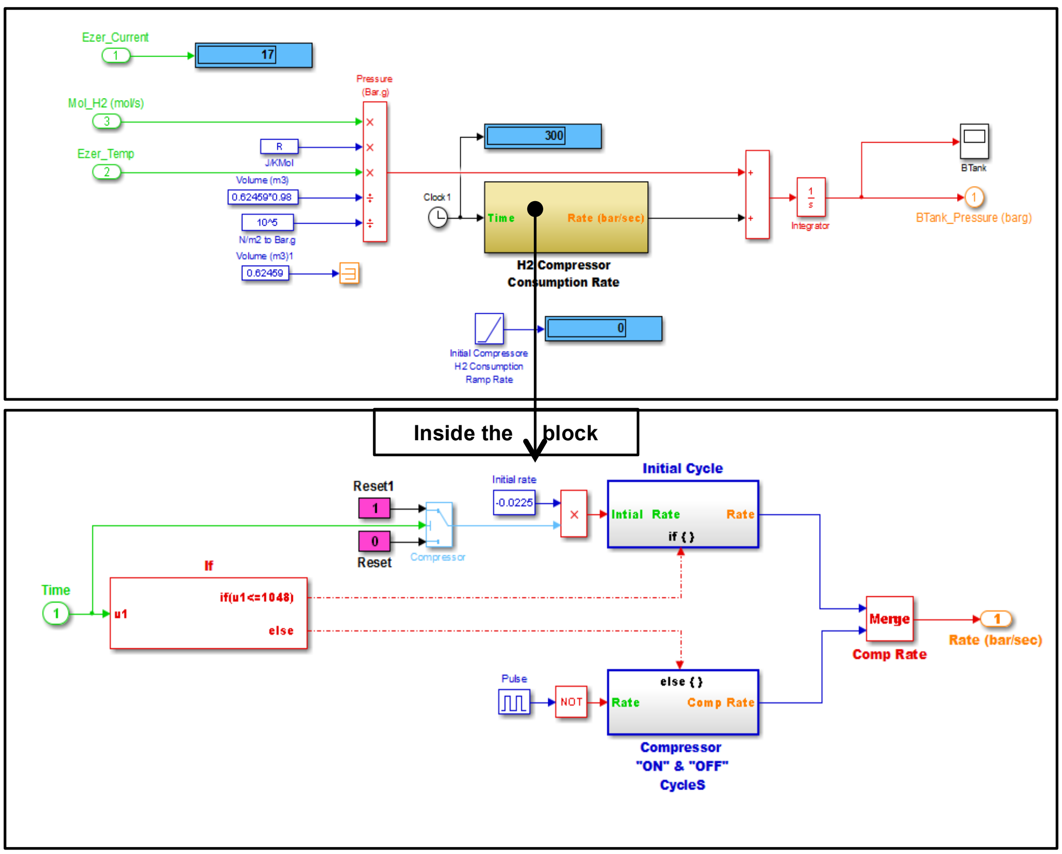

Figure 17: Compressor cycle model inside the buffer tank block

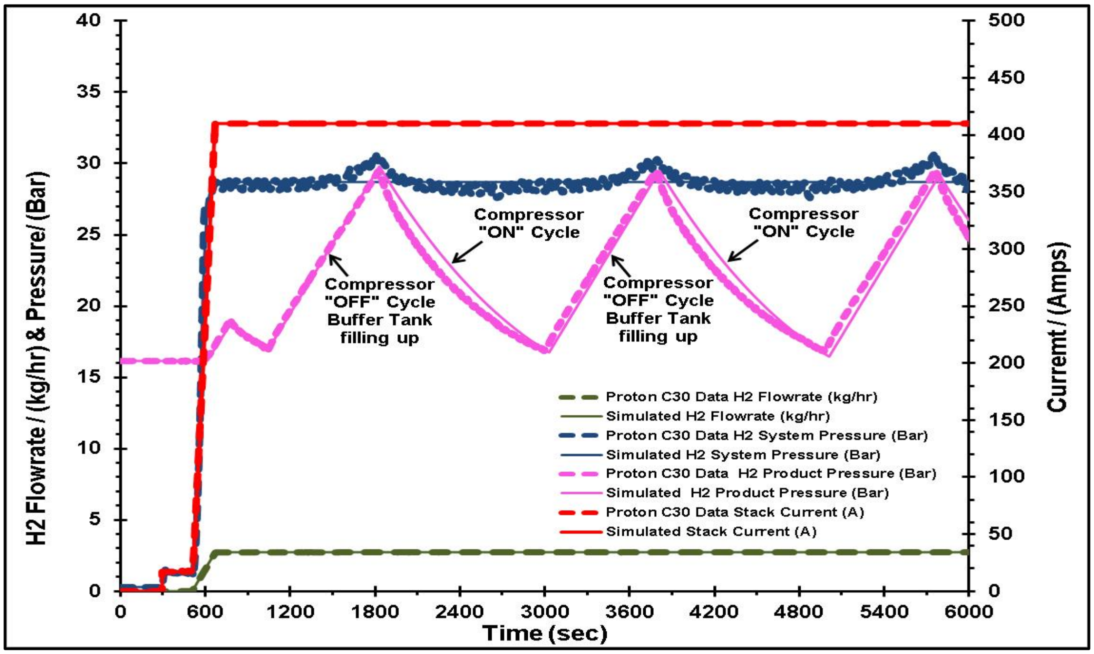

Figure 18: Simulated compressor cycle results compared with data from the Proton C30 electrolyzer

Grid Power System Model:

The grid power system model includes a dynamic frequency model with primary-controlled power plant. Figure 19 shows the model of the grid power system in the Simulink environment. The main control objective of the grid power system model is to maintain the balance between the electric power produced by the generators and the power consumed by the loads, including the network losses, at all time instants. If this balance is not kept, this will lead to frequency deviations that if too large will have serious impacts on grid system operation.

The dynamic frequency model (DFM) based on the swing equation $[\Delta f=\int(f_0/2HS_B)\times(P_m-P_e)]$ for the set of synchronous machines (generators), is used to determine the change in average system frequency (Δf) and is defined as the "center of inertia of the system". This algorithm is valid for reasonable frequency deviations due to imbalances between the instantaneous generation and consumption of electric power which has an accelerating or decelerating effect on the synchronous machines.

The DFM also includes aggregated system loads (**$1/D_F$**) and large rotating motor loads (**W_0**) which are depending directly on the frequency. These loads are evidently present in a real power system and have a stabilizing effect on the system frequency.

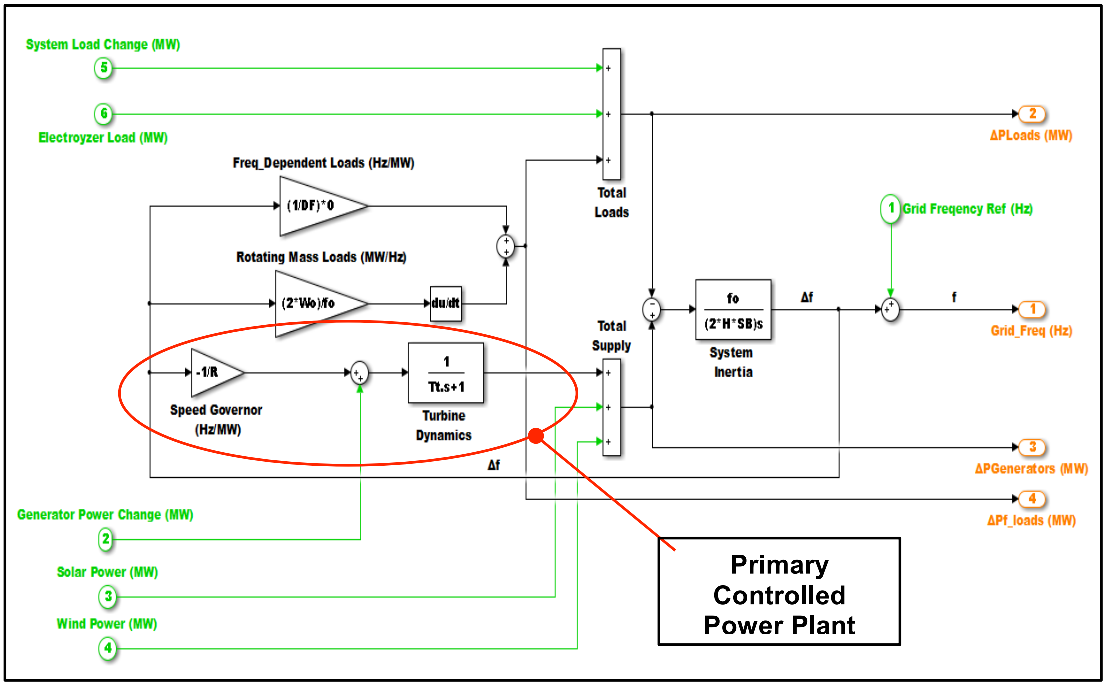

Figure 19: Grid Power System Simulink block with dynamic frequency model with the primary controlled power plant.

The values of $\mathbf{W_0}$ and $\mathbf{D_F}$ are obviously highly dependent on the structure of the load and can be variable over time. Especially, $\mathbf{W_0}$ is only a factor in power systems with large industrial consumers running heavy rotating machines. The constant $\mathbf{D_F}$ has typical values such that the variation of the load is equal to 0-2% per % of frequency variation.

The primary controlled power plant is also part of the grid power system model as shown in Figure 19. This power plant model includes a primary frequency controller also known as the speed regulation of the governor or Speed Governor and Turbine Dynamics. The primary control refers to control actions that are done locally (on the power plant level) based on the set points for frequency and power. The actual values of these can be measured locally, and deviations from the set values result in a signal that will influence the valves, gates, servos, etc. The purpose of the speed governor is to bring the frequency back to acceptable values. However, since the controller is implemented on a local level, the controller cannot have an integral component, but only proportional control which will always have some unavoidable frequency control error.

The turbine dynamics also play an important role in the overall dynamic response of the system. The delay between the different parts of the steam path in the turbine system is usually modeled by a number of first order filters depending on the number of turbines (high to intermediate to low pressure ones) and re-heaters used in the system. Typical values of the time constant of the delay between the control valves and the high-pressure turbine is 0.1 − 0.4 seconds. If a re-heater is installed, the time delay is larger typically 4 − 11 seconds. The time constant of the delay between the intermediate and low pressure turbines is in the order of about 0.3 − 0.6 second. For simplicity and for initial investigation, only one first order filter of Tt = 0.3 second is used in the grid power system model. However, the model can be customized to different configurations of power systems (gas, hydro, etc.) used on the Island of Hawaii.

To understand the behavior and dynamic characteristic of the grid power system model, different step changes in supply and load power signals were input into the model. The simulation was run for 300 seconds and the following parameters were used in the time domain simulation:

- Total System Rating, $\mathbf{S_B}$ = 4000 MW
- Total system inertia constant, **H**.= 5 sec
- Nominal Frequency, $\mathbf{f_o}$ = 60 Hz
- Frequency dependent load
    - constant, $\mathbf{D_F = (f_o/S_B)}$ = 0 Hz/MW (***Zero for this investigation***)
- Rotating Mass load
    - constant, $\mathbf{W_0}$= 0 MW/Hz (***Zero for this investigation***)
- Speed Governor (proportional control)
    - constant, $\mathbf{R = (4/100)*(f_o/S_B)}$ = $6e^{-04}$ Hz/MW
- Turbine Time constant, $\mathbf{T_t}$ = 0.3 sec
- Input Power Signals:
    - The plot below shows the step change in **Solar Power**, **System Load** and **Electrolyzer Load**. The **generator power** and **wind power** had no step change in power during the 300 second simulation:

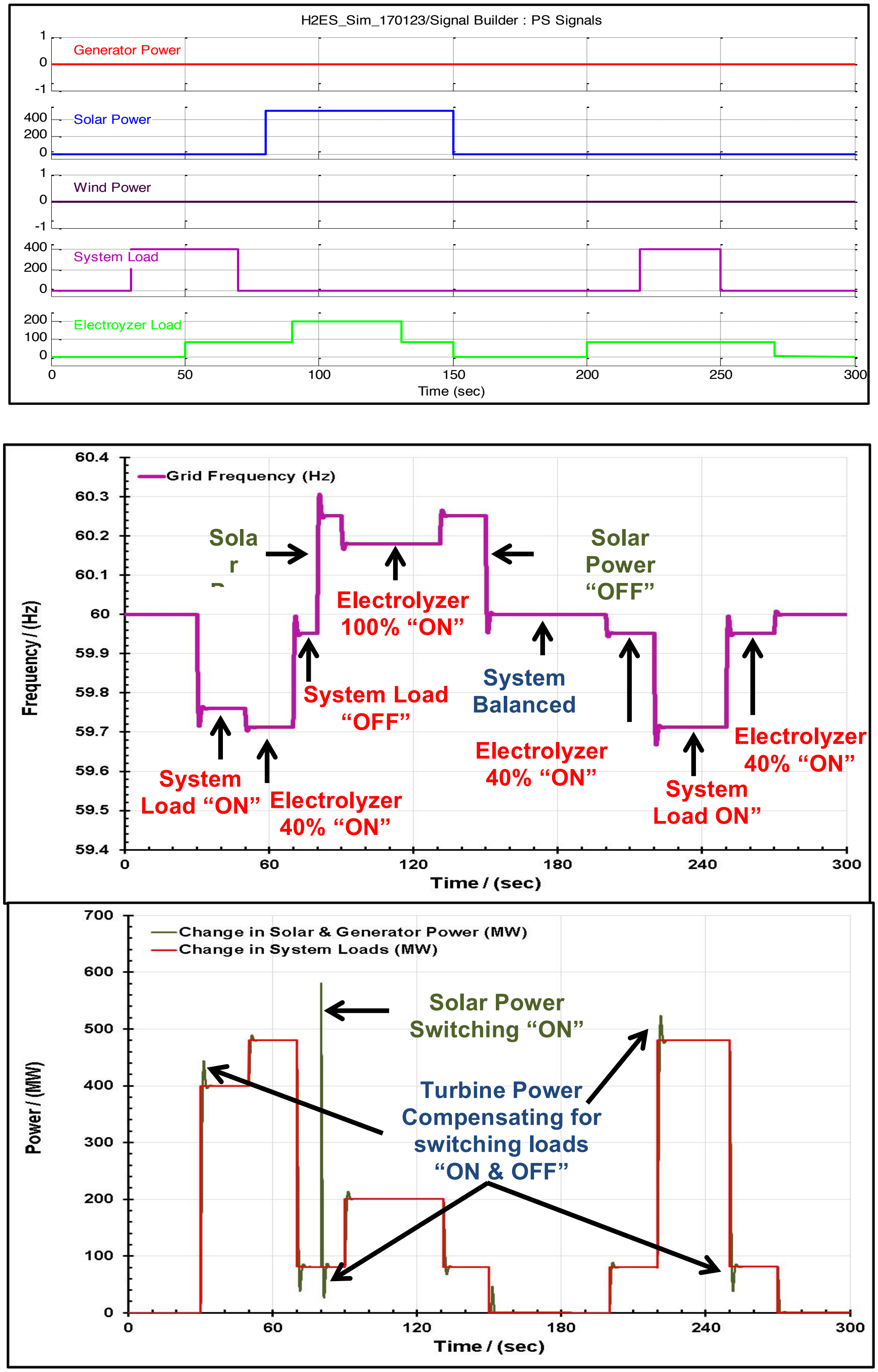

Figure 20: Simulated results from the grid power system model for different step change input power signals

Figure 20 shows the frequency (top) and power (bottom) response of grid power system model to step changes in the system load, electrolyzer load and solar power over the 300 second simulation. For the first 30 sec the system is balanced and there is no change in frequency remaining constant at 60 Hz. After that the power system responds to the change in system and 40% electrolyzer loads. The effect of the primary frequency controller is also observed whereby the controller is increasing the turbine power to compensate for increase in load demand.

When solar power is available at the 80th second, the frequency increases to above 60 Hz and that would give an indication to our grid management control algorithm (**yet to be designed**) to ramp up the electrolyzer power to produce more hydrogen since there is excess power available. This action is done manually in this investigation, as the electrolyzer demand load is increased to 100%. Once the solar power is no longer available and the electrolyzer is ramped down (may be due to full storage tanks), the frequency returns to 60 Hz and the system is now in a balanced state once again as seen in Figure 20 after the 150 second time period.

Next Steps

The next steps in the development of the HES Simulation are the battery model, grid management control algorithm and the HES Simulation system studies using realistic load profiles under different operational and control strategies.