FUEL CELL STACK USER'S MANUAL

Version 1.1

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1 Introduction

Fuel cell performance is affected by several design and operating parameters. It is important to understand these relationships to design a good fuel cell system. Emmeskay, Inc. has developed a simulation model that can be used for this purpose. The model simulates the thermo-electro-chemical phenomena occurring in the fuel cell. Typical usage scenarios for the fuel cell stack model include:

- Sensitivity studies
    - Evaluation of the impact of the stack operating pressure and the stack temperature on the fuel cell performance.
    - Investigation of the impact of fuel processor lag on the fuel cell performance.
- Model based control system development
    - Design and verification of model based control systems for air and fuel supply.
- Performance trade-off analysis
    - System level optimization studies to determine optimal operating conditions.
    - Trade-off analysis to arrive at optimal air supply strategy.
- Specification flow down
    - Coolant controller performance specification for desired fuel cell operation.
    - Actuator and sensor performance specification for desired fuel cell performance.

2 Quick Start

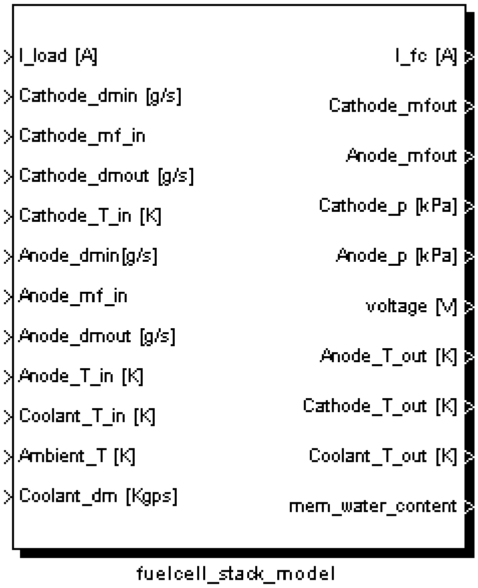
To help understand the fuel cell stack model, a demo fuel cell system model is provided. This section describes how one can quickly start MATLAB® and run the fuel cell demo model. The demo model details are given in section 4. Follow these step-by-step procedures to run the fuel cell demo model.

1. Start MATLAB® and change the directory to the folder where the fuel cell demo model is saved.
2. Open the model by typing “fuelcellmodel_uddc_model” in the MATLAB® command window. This will open the Simulink® model in a separate window.
3. Initialize the model by typing “init_fuelcell” in the MATLAB® command window.
4. Initialize the desired power cycle profile by double clicking the “DubleClick2Load” block in the Simulink model window.
5. Simulate the model by pressing “start simulation” button in the Simulink® toolbar.
    a. If you are running the model for the first time, a new window will pop up with the license agreement. Read the license agreement carefully. The model will simulate after you accept the license agreement.
6. Simulation results can be viewed by opening the scope blocks.

3 Fuel Cell Stack Model

Emmeskay's fuel cell stack model simulates the thermo-electro-chemical phenomena occurring in the fuel cell. This model computes the fuel cell stack electrical performance, outlet temperatures and membrane water content given the inlet flow, temperature and molefractions, and load current. This model is available in the MATLAB®/Simulink® platform.

Figure 1: Fuel cell stack model library



Port Labeling Convention: The name of the signal and its units (where applicable) are shown in the port names. The units of the signal appear within "[ ]". As an example, the port name 'Cathode_dmin [g/s]' represents Cathode inlet stream mass flow rate in units of grams/second.

3.1 Model Features

The salient features of this model are:

- Primarily models PEM fuel cells
- Pressure dynamics in anode and cathode
- Water transport across the membrane
  - Driven by electro-osmotic drag and diffusion due to the concentration gradients
- Water evaporation/condensation in the cathode due to relative humidity
- Heat generation in the fuel cell stack
  - Computed from the electrical energy produced and theoretical energy available
  - The total energy produced is divided between the anode and cathode based on user input
- Thermal balances in anode, cathode and coolant includes the heat transfer between anode, cathode, coolant and ambient
- Ideal fuel cell voltage (Open Circuit Voltage)
  - Computed from the fuel cell temperature, hydrogen and oxygen partial pressures
- Voltage losses due to the activation, Ohmic and concentration overpotentials

3.2 Model Inputs/Outputs

No.	Signal Name	Type	Units	Description
1	I_load	Input	Amperes	Load current
2	Cathode_dmin	Input	grams/sec	Cathode inlet stream mass flow rate
3	Cathode_mf_in	Input	Fraction	Cathode inlet stream mole fraction
4	Cathode_dmout	Input	grams/sec	Cathode outlet stream mass flow rate
5	Cathode_T_in	Input	Kelvin	Cathode inlet stream temperature
6	Anode_dmin	Input	grams/sec	Anode inlet stream mass flow rate
7	Anode_mf_in	Input	Fraction	Anode inlet stream mole fraction
8	Anode_dmout	Input	grams/sec	Anode outlet stream mass flow rate
9	Anode_T_in	Input	Kelvin	Anode inlet stream temperature
10	Coolant_T_in	Input	Kelvin	Coolant inlet stream temperature
11	Ambient_T	Input	Kelvin	Ambient temperature
12	Coolant_dm	Input	Kilograms/sec	Coolant stream mass flow rate
13	I_fc	Output	Amperes	Fuel cell current [Current supplied by the fuel cell. This will be equal to the load current most of the times except when there are not enough reactants present in the fuel cell]
14	Cathode_mfout	Output	Fraction	Cathode outlet stream mole fraction
15	Anode_mfout	Output	Fraction	Anode outlet stream mole fraction
16	Cathode_p	Output	kiloPascals	Cathode pressure
17	Anode_p	Output	kiloPascals	Anode pressure
18	voltage	Output	Volts	Fuel cell stack voltage
19	Anode_T_out	Output	Kelvin	Anode outlet stream temperature
20	Cathode_T_out	Output	Kelvin	Cathode outlet stream temperature
21	Coolant_T_out	Output	Kelvin	Coolant stream outlet temperature
22	mem_water_content	Output	dimensionless	Membrane water content [defined as the ratio of number of water molecules to the number of sulphonic acid groups in the membrane]

3.3 Model Parameters

The fuel cell model parameters are divided into five vectors namely “mem”, “ht”, “cat”, “geo” and “ic”. They are as follows

Table 1: mem – vector consisting of the membrane properties

No.	Parameter	Units	Description

1	mem(1)	grams/mol of SO_3^-	Membrane equivalent weight [defined as weight of the membrane per mole of sulphonic acid group i.e. SO_3^-]
2	mem(2)	grams/cm^3	Membrane dry density

Table 2: ht – vector consisting of the heat transfer coefficients

No.	Parameter	Units	Description
1	ht(1)	Fraction	Fraction of the total heat generated in the cathode
2	ht(2)	Watts/Kelvin	Heat transfer coefficient for heat transfer between anode and cathode
3	ht(3)	Watts/Kelvin	Heat transfer coefficient for heat transfer between fuel cell and surroundings
4	ht(4)	Watts/Kelvin	Heat transfer coefficient for heat transfer between fuel cell and coolant
5	ht(5)	Joules/Kelvin	Product of coolant volume, density and specific heat
6	ht(6)	Kilograms	Product of coolant volume and density

Table 3: cat – vector consisting of the catalyst properties

No.	Parameter	Units	Description
1	cat(1)	cm^2/gram	Catalyst surface area (electrode)
2	cat(2)	milligram/cm^2	Catalyst loading in the electrodes
3	cat(3)	dimensionless	Catalyst utilization

Table 4: geo – vector consisting of the cell geometry

No.	Parameter	Units	Description
1	geo(1)	dimensionless	Number of cells in the fuel cell stack
2	geo(2)	cm^2	Cell active area
3	geo(3)	cm	Membrane thickness
4	geo(4)	cm^3	Membrane equivalent volume
5	geo(5)	m^3	Cathode equivalent volume
6	geo(6)	m^3	Anode equivalent volume

Table 5: ic – vector consisting of the initial conditions

No.	Parameter	Units	Description
1	ic(1)	moles	Initial condition for anode stream

			[should be greater than 1e-07]
2	ic(2)	moles	Initial condition for cathode stream [should be greater than 1e-07]

3.4 Model Scope

- Software
  - Works only with the variable time step algorithms in Simulink.
  - Zero crossings detection should be turned off to increase the simulation speed.
  - Not compatible with MATLAB® versions 5.3.1 (R11.1) and below.
- Technical
  - Model is a lumped parameter model and does not include spatial dependence of the states.
  - Temperature dependence of concentration overpotentials is not captured.
  - Water formed in the cathode is in the liquid state.
  - Model is restricted to Nafion membranes only.

3.5 Instructions for using the Model

The fuel cell stack model is available as a library element. This model block can be incorporated into Simulink® model by two ways. They are

- Copying the library element and then pasting the element in the destination Simulink® model
- By dragging and dropping the library element into the destination Simulink® model

After incorporating the fuel cell stack block into the model, the next step is to initialize the model parameter data. The default model initialization data is available in the "init_fuelcell.m" script file. This script file can be invoked by typing the name in the MATLAB® command window. The model parameter data can be changed in the script file.

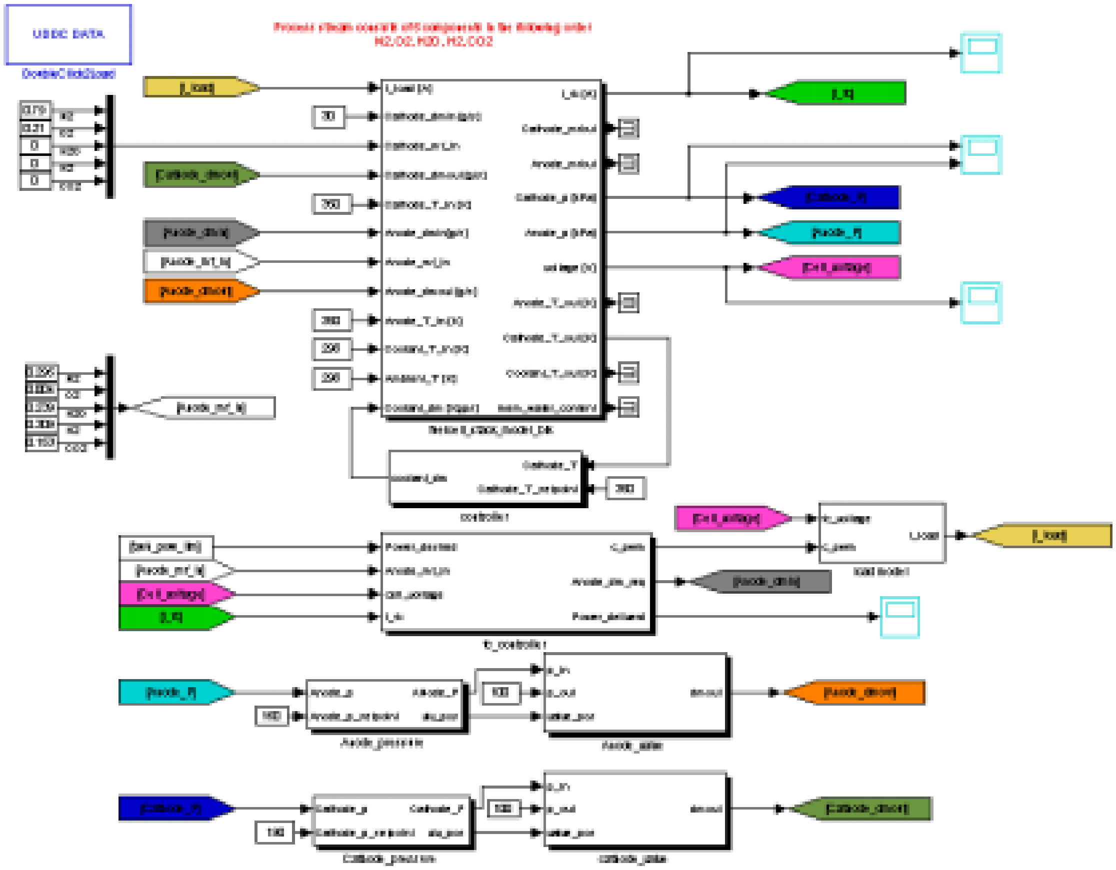
4 Fuel Cell Demo Model

The objective of the demo model is to illustrate the use of the fuel cell stack model in a typical usage scenario. The fuel cell demo model consists of fuel cell stack block, valves for anode and cathode, controller for anode and cathode, fuel cell controller (fc_controller) subsystem and a load system.

The fuel cell controller attempts to schedule the fuel flow through the anode such that the power required to follow an Urban Dynamometer Drive Schedule (UDDS) is achieved from the fuel cell.

The inputs to the demo model are UDDS power, cathode inlet flow rate, mole fraction and temperature, anode inlet mole fraction and temperature, ambient temperature and coolant inlet temperature. Table 6 describes the functions of each of the subsystems. Snapshot of the fuel cell demo model is shown below.

Figure 2: Fuel Cell Demo Model



4.1 *Various Blocks in the Fuel Cell Demo Model*

Table 6: Various subsystems in Fuel cell Demo Model

No.	Block Name	Purpose	Description
1	fuelcell_stack_model_blk	Simulates fuel cell stack behavior	Computes the stack electrical performance, outlet mole fractions, temperatures and pressures
2	fc_controller	Controls the stack inlet flow rate	Computes the anode inlet mass flow rate and PWM command to load model using the UDDS power and stack voltage
3	Anode_valve	Simulates the anode outlet valve	Computes the anode outlet flow rate using the anode pressure, exhaust pressure and valve position

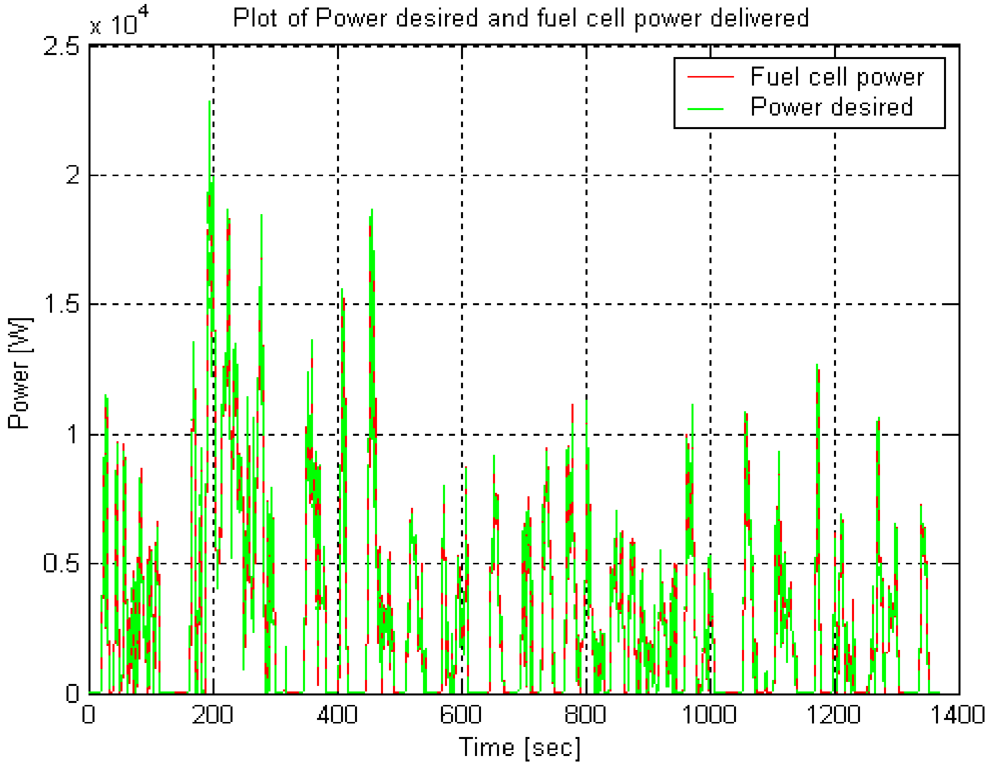
4	Anode_pressure	Controls the anode pressure	Computes the anode outlet valve position using the anode pressure and set point pressure
5	cathode_valve	Simulates the cathode outlet valve	Computes the cathode outlet flow rate using the cathode pressure, exhaust pressure and valve position
6	Cathode_pressure	Controls the cathode pressure	Computes the cathode outlet valve position using the cathode pressure and set point pressure
7	controller	Controls the cathode temperature	Computes the coolant flow rate using the cathode temperature and set point.
8	load model	Simulates the electric load	Computes the load current using the fuel cell voltage and pwm command

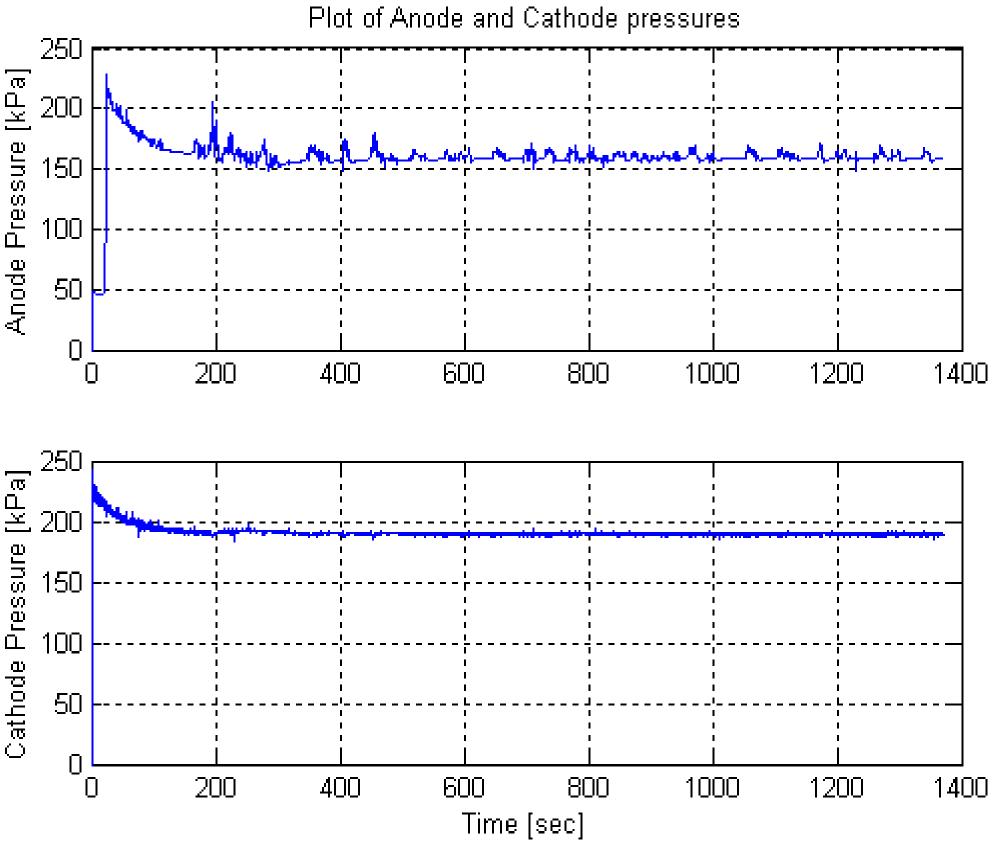
4.2 Instructions for running the Demo Model

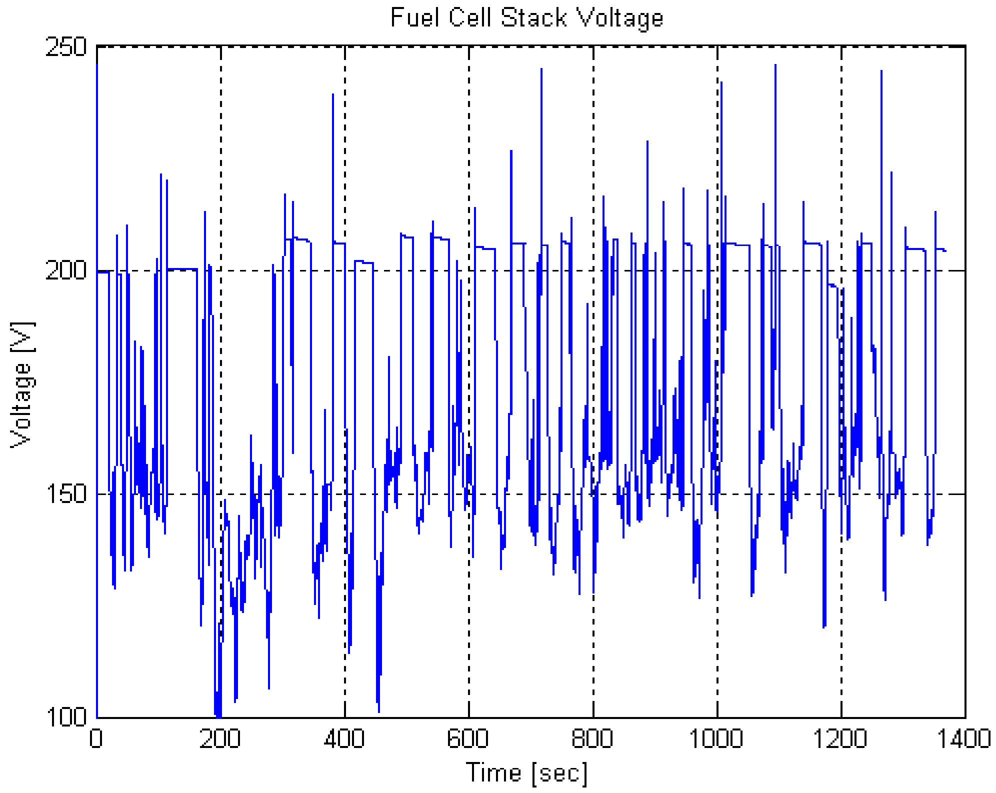
1. Initialize the model parameters by invoking the script file "init_fuelcell".
2. Open the Simulink$^{®}$ model by typing "fuelcellmodel_uddc_model" in MATLAB$^{®}$ command window.
3. Load the UDDS data by double clicking the "DubleClick2Load" block in the Simulink$^{®}$ model.
4. Simulate the model by pressing "start simulation" button in the Simulink$^{®}$ toolbar.

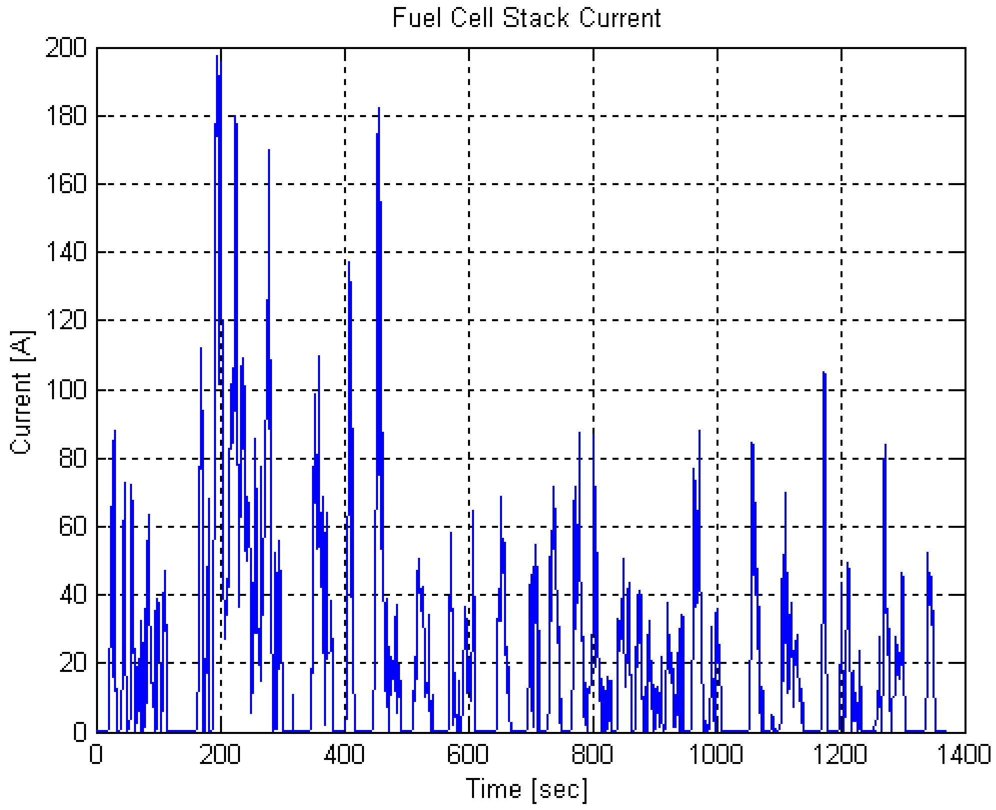
4.3 Sample Demo Model Results

Results of the simulation are given in the following figures.


Plot of Power desired and fuel cell power delivered
x 10^4
Fuel cell power
Power desired
Power [W]
0
0.5
1
1.5
2
2.5
0
200
400
600
800
1000
1200
1400
Time [sec]


Plot of Anode and Cathode pressures
Anode Pressure [kPa]
Cathode Pressure [kPa]
0
50
100
150
200
250
0
200
400
600
800
1000
1200
1400
Time [sec]


Fuel Cell Stack Voltage
Voltage [V]
250
200
150
100
0
200
400
600
800
1000
1200
1400
Time [sec]


Fuel Cell Stack Current
Current [A]
200
180
160
140
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
Time [sec]

5 About the company

Emmeskay, Inc. is a rapidly growing dynamic company offering state-of-the-art technology products and services in the area of systems engineering for automotive and environmental applications. Our vision is to be recognized as a world-class systems engineering products and services provider, and to become the partner of choice in our customer's realization of "model based design processes". We have several man–years of experience in modeling, simulation, control algorithm development, and optimization with several of those years in the automotive vehicle and powertrain areas.

For technical support, please send an email to fcstackmodel@emmeskay.com with "fuel cell stack model" in the subject line.

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