Labview Based Sliding Mode Voltage Control of PEM Fuel Cell System

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Abstract—This paper presents the simulation of a dynamic model of PEM (Proton Exchange Membrane) fuel cell in Matlab and Labview which provides an easy to use and understand simulator with GUI. The open circuit output voltage, activation losses, ohmic losses, concentration losses and temperature dynamics are modeled and analyzed for change in the input parameters. Power conditioning unit for the cell are modeled and control strategy is implemented for them. The simulation results are then scaled down for hardware implementation.

Index Terms—PEM fuel cell, boost converter, labview

I. INTRODUCTION

The increasing rate of depletion of the non-renewable resources and the resulting energy crisis has increased the urge of developing and enhancing the utilization of renewable sources. PEM (Proton Exchange Membrane) Fuel cells pose to be a strong candidate in answer to these increasing power requirements and to maintain balance between ecology and development.

The very idea of commercialization of the fuel cell technology has ever since its invention has led to immense research and experimentation. Improved dynamic models are being developed so as to imitate the various electrochemical, thermo dynamic and chemical kinetics phenomenon of the PEM fuel cell as closely as possible.

A dynamic model for PEM fuel cell developed in [1] and simulated in Simulink and PSPICE show close agreement with the experimental results. The state-space model developed in [2] based on [1] aims at developing a control oriented model for a 500 W, 48 cell stack and its validation against the experimental results. Reference [3] attempts to model a overall PEM fuel cell distributed system. Section III models the power conditioning unit and its sliding mode control (SMC) design. Section IV presents the simulation results of the model in Simulink and Labview. In Section V the experimental set up is explained. Finally Section VI concludes the results.

II. PEM FUEL CELL MODELING

The individual components of the fuel cell system the various governing laws for each of these components and their interaction with each other make the fuel cell system very complex and sophisticated. Thus, to avoid complications in the analysis, the model is based on certain assumptions like ideal behavior of gases, uniform distribution of species and no temperature and pressure variations for the system.

The PEM fuel cell is an electrochemical device in which the oxidation of hydrogen occurring at anode liberates free electrons and hydrogen ions which move through the external circuit and membrane respectively. The reduction of oxygen at cathode utilizes the protons and electrons reaching it to form water.

Anode oxidation : \(2H_2 \rightarrow 4H^+ + 4e^-\)
Cathode reduction : \(O_2 + 4H^+ + 4e^- \rightarrow 2H_2O\)
Overall cell reaction : \(2H_2 + O_2 \rightarrow 2H_2O\)

A. Steady - State Model

Steady-state model is the analysis of the behavior of fuel cell for a particular instant of time keeping the input parameters temperature, anode and cathode channel pressures constant. Changing one parameter, while keeping others constant enables us to figure out the effect of change in one parameter on others and hence their relation.

The reversible single cell potential \(E_{cell}\) is given as [2]:

\[
E_{cell} = E_{cell}^0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2}}{P_{H_2O}} \sqrt{\frac{P_{O_2}}{P_{H_2O}}} \right)
\]

\(E_{cell}^0\) is the standard cell potential in ideal conditions without considering any losses. This is the ideal voltage output which a cell would deliver if all the Gibb’s free energy could be converted into electrical energy. Practically due to many operational losses the actual output voltage is always less than the standard voltage.

Mainly three losses are dominant in fuel cell operation, namely:

Section II comprises of modeling the PEM fuel cell system. Section III models the power conditioning unit and its sliding mode control (SMC) design. Section IV presents the simulation results of the model in Simulink and Labview. In Section V the experimental set up is explained. Finally Section VI concludes the results.

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Mainly three losses are dominant in fuel cell operation, namely:
1. Activation Losses ($V_{act}$)
2. Ohmic Losses ($V_{ohm}$)
3. Concentration Losses ($V_{conc}$)

Each of these losses dominate at a particular phase of cell operation. During initial startup, the voltage lost in overcoming the activation energy of the reactants and the electrodes lead to activation losses which is a function of current (I) and cell temperature (T). It is non-linear in nature and given by [1]:

$$V_{act} = \frac{RT}{2F} \ln \left[ \frac{I}{I_a} \right]$$  \hspace{1cm} (2)

The resistance offered by the electrodes as well as the membrane to the movement of electrons and ions across the channel causes linear ohmic losses given by:

$$V_{ohm} = IR_o$$  \hspace{1cm} (4)

The resistance offered is also a function of temperature and current expressed as [1]:

$$R_o = R_{ac} + K_I I - K_F$$  \hspace{1cm} (5)

As the reaction proceeds, and the load increases, the rate of reaction and hence the consumption of the reactants increases to meet the demand. This leads to formation of concentration gradient along the channel and cause concentration losses governed by equation [1]:

$$V_{conc} = \frac{RT}{2F} \ln \left[ 1 - \frac{I}{i_l} \right]$$  \hspace{1cm} (6)

Thus the net open-circuit voltage output ($V_{fc}$) for unit cell is given by:

$$V_{fc} = E_{cell} - (V_{act} - V_{ohm} - V_{conc})$$  \hspace{1cm} (7)

B. Dynamic Model

As the reaction progresses with time the parameters of the system are no longer constant but dynamic. The dynamism incorporated by each parameter is decided by its respective governing equation which can be formulated from the laws of conservation of mass, energy, momentum and other basic sciences. Hence the rate of change parameters with respect to time is formulated, which makes it possible to determine the value of parameter at any given instant of time for given initial conditions. The main fuel cell parameters temperature, pressure, flow and humidity are generally considered for dynamic analysis.

1) Flow dynamics

Applying molar balance to individual species we have the net molar flow rates of hydrogen, oxygen and water as [2]:

$$\left( \frac{d(m_{H_2})_{net}}{dt} \right) = \frac{1}{2F} \left[ \frac{I}{2} - (m_{H_2})_{net} \right]$$  \hspace{1cm} (8)

$$\left( \frac{d(m_{O_2})_{net}}{dt} \right) = \frac{1}{2F} \left[ \frac{I}{4} - (m_{O_2})_{net} \right]$$  \hspace{1cm} (9)

$$\left( \frac{d(m_{H_2}O)_{net}}{dt} \right) = \frac{1}{2F} \left[ \frac{I}{2} - (m_{H_2}O)_{net} \right]$$  \hspace{1cm} (10)

2) Pressure dynamics

Similar application of ideal gas law, based on the assumption of ideal gas behavior gives the rate determining equations for the partial pressure of the reacting species [2]:

$$\frac{dP_{H_2}}{dt} = 2\theta_1U_{pa} - 2\theta_1 \frac{dP_{O_2}}{dt} - \theta_2 I$$  \hspace{1cm} (11)

$$\frac{dP_{O_2}}{dt} = 2\theta_2U_{pe} - 2\theta_3 \frac{dP_{H_2}}{dt} - \theta_4 I$$  \hspace{1cm} (12)

$$\frac{dP_{H_2O}}{dt} = 2\theta_5 \frac{dP_{H_2}}{dt} + 2\theta_4 \frac{dP_{O_2}}{dt}$$  \hspace{1cm} (13)

where, $\theta_1, \theta_2, \theta_3, \theta_4, \text{and} \theta_5$ are as in [2].

3) Temperature dynamics

Fuel cell reaction being an exothermic reaction generates heat, which is a crucial issue for fuel cell operation point of view, as it affects other operating parameters and component’s characteristics drastically. Increase in temperature starts dehydrating membrane and polarization curve shifts upwards indicating decrease in cell losses. Thus an optimum temperature is required for fuel cell operation. From [1], [2], [5], [6], [8] the net heat cell losses. Thus an optimum temperature is required for fuel cell operation. From [1], [2], [5], [6], [8] the net heat generation in the system is the sum of all the heat generated minus the total heat lost from the system. Heat is generated in PEM fuel cell only due to the electrochemical reaction ($Q_{chem}$) occurring, but heat losses occur from the system due to convective heat transfer of air ($Q_{conv}$), heat generated due to the electrical output power ($Q_{elec}$) and heat removed from the system by the coolant ($Q_{cool}$), in case of cooling provided. Temperature dynamics, thus can be modeled as [2]:

$$M_{fc}C_{fc} \frac{dT}{dt} = \dot{Q}_{net}$$  \hspace{1cm} (14)

$$\dot{Q}_{net} = \dot{Q}_{chem} - \dot{Q}_{elec} - \dot{Q}_{conv} - \dot{Q}_{cool}$$  \hspace{1cm} (15)

Assuming no cooling in the system,

$$\frac{dT}{dt} = \frac{\dot{Q}_{chem} - \dot{Q}_{elec} - \dot{Q}_{conv}}{M_{fc}C_{fc}}$$  \hspace{1cm} (16)

where, the rate of heat generation due to electrochemical reaction is directly related to the rate of reaction taking place and is given as:

$$\dot{Q}_{chem} = \theta_6 I$$  \hspace{1cm} (17)

The generation of heat due to electrical output power is a function of voltage and current of the cell and is given as:

$$\dot{Q}_{elec} = V_{fc} I = \theta_7 I$$  \hspace{1cm} (18)

Heat loss due to convection is a result of the difference in the temperature of the ambient environment and the cell:

$$\dot{Q}_{conv} = (T - T_a)h_aA_s$$  \hspace{1cm} (19)

Substituting and rearranging, finally results in:

$$\frac{dT}{dt} = \left[ - \frac{h_aA_s}{M_{fc}C_{fc}} \right] \theta_8 I + \left[ - \frac{h_uA_s}{M_{fc}C_{fc}} \right] U_{Tr}$$  \hspace{1cm} (20)

where, $\theta_6, \theta_7, \text{and} \theta_8$ are as in [2].
III. POWER CONDITIONING UNIT MODELING AND CONTROL

To match the type and the correct voltage ratings of the load to be supplied by the fuel cell output we need power conditioning unit [7].

A. Dc-Dc Converter Modeling and Control

Using state-space averaging method dc-dc boost converter can be modeled as [7]:

\[
    x_1 = -(1 - u) \left( \frac{1}{L_{bc}} \right) x_2 + \left( \frac{V_{fc}}{L_{bc}} \right)
\]

\[
    x_2 = -(1 - u) \left( \frac{1}{C_{bc}} \right) x_1 - \left( \frac{1}{C_{bc} R_{bc}} \right) x_2
\]

where, equation variables are as labeled in Fig. 1 and \( x_1 = I_{L,bc} \) is the current from the fuel cell input to the boost converter and \( x_2 = V_{c,bc} \) is its output to load.

A sliding mode cascade controller (SMC) shown in Fig. 2 is designed with voltage as controlled variable in the outer and current in inner loop, using the integrator backstepping method or regular form control, with the control goal to achieve a constant steady-state output voltage:

\[
    x_2 = V_{dc,ref}
\]

\[
    \dot{x}_2 = V_{dc,ref} = 0
\]

The desired current (\( x_1^{*}_{bc} \)) to meet the reference voltage (\( V_{dc,ref} \)) is:

\[
    x_1^{*}_{bc} = \frac{V_{dc,ref}^2}{R_{bc} V_{fc}}
\]

Sliding surface (\( s \)) for current control should be as:

\[
    s = x_1 - x_1^{*}_{bc}
\]

The control (\( u \)) designed to achieve sliding (enforcing \( x_1 \) to track \( x_1^{*}_{bc} \)) is:

\[
    u = \left( \frac{1}{2} \right) \left[ 1 - \text{sign}(s) \right]
\]

B. Inverter Modeling and Control

The continuous time state-space model of a single phase full bridge inverter is given by:

\[
    \dot{x}_p = Ax_p + Bu
\]

\[
    y = Cx_p + Du
\]

This continuous simulink model, shown in Fig. 3 is discretized in Matlab at 25ms sampling time and a cascade discrete PID control is implemented for it with load voltage across \( R_l \) and \( C_l \) as the controlled output in the outer loop and \( I_{inv} \) in inner loop. The rate of change of current being greater than voltage it forms the inner loop with voltage in the outer loop. The system variables are labeled in Fig. 3.

The dynamic model of the system developed in section II and III is simulated in Simulink and Labview. The value of parameters for static and dynamic simulation is taken for the Avista Labs SR-12 PEM fuel cell stack and the results are validated with its experimental results of [1]. The dynamic output of the fuel cell model is fed to the boost converter model and sliding mode control strategy is simulated for controlling its output voltage.
C. Matlab/Simulink Simulation

Simulation of SMC to regulate fuel cell output voltage at the boost converter end shows regulated voltage (Fig. 5) and current response (Fig. 6). The control output of SMC, shown in Fig. 7 is given to regulate the duty cycle of the boost converter which gives corresponding voltage output. The chattering of the sliding surface can be seen in Fig. 4.

![Sliding Surface s =0](image)

**Figure 4. Sliding Surface s =0**

![Boost converter output voltage versus time](image)

**Figure 5. Output voltage of Dc-Dc boost converter**

![Boost converter current output versus time](image)

**Figure 6. DC Output current**

![Control U versus time](image)

**Figure 7. Control switching pattern**

V. HARDWARE IMPLEMENTATION

At NCL laboratory a single cell, nafion membrane PEM fuel cell is fabricated. Simulation parameters are scaled down for single cell operation and hardware parameters are used accordingly. The output of the cell is in the range of 0.5-1 V depending on the loading of the catalyst used. This output is then fed to the boost converter input circuit. The boost converter current and voltage parameters are acquired using NI 9237 DAQ card, shown in Fig. 8 hardware set up. SMC equations implemented using Labview (Fig. 9) takes real time input signals using analog I/O card and depending on the error, generates the control action to enforce the output to track the reference. The control signal governs the duty cycle of the boost converter which in turn manipulates output voltage of the boost converter.

![Experimental setup](image)

**Figure 8. Experimental setup**

The fuel cell dynamic model developed in section II is also simulated in Labview, so that in the absence of hardware the voltage generated from the model can be simulated. It can be used as a stand-alone simulator for study and analyses.

The NCL single PEM fuel cell electrodes are made by brush coating the platinised–carbon catalyst slurry on the gas diffusion layers (GDL). Cathode is generally of higher loading of catalyst than the anode in order to speed up the sluggish reduction reaction which slows down the overall reaction process. The slurry consists of calculated amount of platinised–carbon catalyst to ensure proper unit area loading. Then hot pressing the nafion membrane between the anode on one side and cathode on the other under heavy load forms the membrane-electrode assembly.
This MEA is then mounted between the graphite bipolar plates having the flow fields engraved on to them to deliver the reactants to the MEA. Gaskets are used to seal the boundaries and avoid the leakage of gases. Gold-plated current collectors are inserted to tap the output voltage.

![Figure 9. Labview back panel of SMC](image)

### VI. CONCLUSION

This paper presents an easy to understand and implement dynamic non-linear response of PEM fuel cell which models the various electrochemical and thermodynamic phenomenon in close agreement with the experimental data. This model can be used as a dynamic simulator for fuel cell experimental purpose. The GUI developed in Labview provides an effective tool for data monitoring, acquisition and testing purposes. Labview provides easy interface to the external hardware circuitry, development and simulation and implementation of various control strategies in it.

### APPENDIX A MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter inductor</td>
<td>( L_f )</td>
<td>25 mH</td>
</tr>
<tr>
<td>Inverter capacitor</td>
<td>( C_f )</td>
<td>100 ( \mu F )</td>
</tr>
<tr>
<td>Inverter frequency</td>
<td>( f )</td>
<td>60Hz</td>
</tr>
<tr>
<td>Inverter input</td>
<td>( V_{dc} )</td>
<td>300V</td>
</tr>
<tr>
<td>Load inductance</td>
<td>( L_i )</td>
<td>15 mH</td>
</tr>
<tr>
<td>Load resistance</td>
<td>( R_i )</td>
<td>5.55Ω</td>
</tr>
<tr>
<td>Standard voltage</td>
<td>( E_{cell} )</td>
<td>1.23V</td>
</tr>
<tr>
<td>Activation loss constants</td>
<td>( a_a )</td>
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<tr>
<td></td>
<td>( a_b )</td>
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<tr>
<td></td>
<td>( b )</td>
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<tr>
<td>Ohmic loss constants</td>
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</tr>
<tr>
<td></td>
<td>( R_{jc} )</td>
<td>-7.5 \times 10^{-6} ( \Omega/K )</td>
</tr>
<tr>
<td></td>
<td>( R_{jc} )</td>
<td>7.85 \times 10^{-3} ( \Omega/A )</td>
</tr>
<tr>
<td>Limiting current</td>
<td>( I_l )</td>
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<tr>
<td>Convective heat transfer coefficient</td>
<td>( h_s )</td>
<td>37.5 W/(m²K)</td>
</tr>
<tr>
<td>Area of single cell</td>
<td>( A_s )</td>
<td>0.032 m²</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>( C_{fc} )</td>
<td>500 J/(molK)</td>
</tr>
</tbody>
</table>

### ACKNOWLEDGMENT

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### REFERENCES


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