

Labview Based Sliding Mode Voltage Control of PEM Fuel Cell System

Bharti Kumari and Ravindra S. Rana

Dept. of Instrumentation & Control, College of Engineering, Pune, India

Email: {atmaja.thakur1, ranaravindra08}@gmail.com

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.

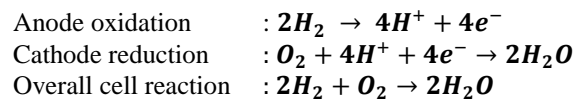
A dynamic model for PEM fuel cell developed in [1] and simulated in Simulink and PSPICE show close agreement with the experimental results. The state-space model developed in [2] based on [1] aims at developing a control oriented model for a 500 W, 48 cell stack and its validation against the experimental results. Reference [3] attempts to model a overall PEM fuel cell distributed system and its control along with its power conditioning unit. A similar state-space approach, based on small-signal modeling is proposed in [4]. In this paper we focus on simulating and analyzing the simplified dynamic model of a PEM fuel cell system in Simulink and Labview. Both being graphical programming languages provide an easy platform for implementation and understanding for a small-scale application. Here we report the laboratory fabrication of single cell unit and its analyses.

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.

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.



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]:

$$E_{cell} = E_{cell}^0 + \frac{RT}{2F} \ln \left[\frac{(P_{H_2})^{1/2} (P_{O_2})^{1/4}}{P_{H_2O}} \right] \quad (1)$$

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:

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]:

$$V_{act} = \frac{RT}{2F} \ln\left[\frac{I}{I_d}\right] \quad (2)$$

$$V_{act} = a_0 + T[a + b \ln(I)] \quad (3)$$

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:

$$V_{ohm} = IR_o \quad (4)$$

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

$$R_o = R_{oc} + K_I I - K_T \quad (5)$$

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]:

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

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

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

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]:

$$\left(\frac{d(mH_2)_{net}}{dt}\right) = \frac{1}{\lambda a} \left[\frac{I}{2F} - (mH_2)_{net}\right] \quad (8)$$

$$\left(\frac{d(mO_2)_{net}}{dt}\right) = \frac{1}{\lambda c} \left[\frac{I}{4F} - (mO_2)_{net}\right] \quad (9)$$

$$\left(\frac{d(mH_2O)_{net}}{dt}\right) = \frac{1}{\lambda c} \left[\frac{I}{2F} - (mH_2O)_{net}\right] \quad (10)$$

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]:

$$\frac{dP_{H_2}}{dt} = 2\theta_1 U_{Pa} - 2\theta_1 \frac{dP_{H_2}}{dt} - \theta_2 I \quad (11)$$

$$\frac{dP_{O_2}}{dt} = 2\theta_3 U_{Pc} - 2\theta_3 \frac{dP_{O_2}}{dt} - \theta_4 I \quad (12)$$

$$\frac{dP_{H_2O}}{dt} = 2\theta_5 \frac{dT}{dt} + 2\theta_4 \frac{dP_{H_2}}{dt} I \quad (13)$$

where, $\theta_1, \theta_2, \theta_3, \theta_4$ and θ_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 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 (\dot{Q}_{chem}) occurring, but heat losses occur from the system due to convective heat transfer of air (\dot{Q}_{conv}), heat generated due to the electrical output power (\dot{Q}_{elec}) and heat removed from the system by the coolant (\dot{Q}_{cool}), in case of cooling provided. Temperature dynamics, thus can be modeled as [2]:

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

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

Assuming no cooling in the system,

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

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

$$\dot{Q}_{chem} = \theta_6 I \quad (17)$$

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

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

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

$$\dot{Q}_{conv} = (T - U_{Tr}) h_s A_s \quad (19)$$

Substituting and rearranging, finally results in:

$$\frac{dT}{dt} = \left[-\frac{h_s A_s}{M_{fc} C_{fc}} \right] - \theta_8 I + \left[-\frac{h_s n_s A_s}{M_{fc} C_{fc}} \right] U_{Tr} \quad (20)$$

where, θ_6, θ_7 and θ_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]:

$$\dot{x}_1 = -(1-u) \left(\frac{1}{L_{bc}} \right) x_2 + \left(\frac{V_{fc}}{L_{bc}} \right) \quad (21)$$

$$\dot{x}_2 = -(1-u) \left(\frac{1}{C_{bc}} \right) x_1 - \left(\frac{1}{C_{bc}R_{bc}} \right) x_2 \quad (22)$$

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.

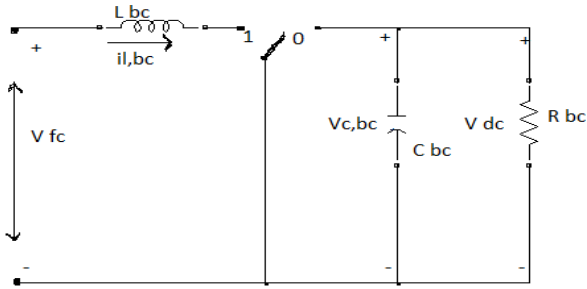


Figure 1. Dc-Dc boost converter

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 back-stepping method or regular form control, with the control goal to achieve a constant steady-state output voltage:

$$x_2 = V_{dc,ref} \quad (23)$$

$$\dot{x}_2 = V_{dc,ref} = 0 \quad (24)$$

The desired current (x_{1bc}^*) to meet the reference voltage ($V_{dc,ref}$) is:

$$x_{1bc}^* = \frac{V_{dc,ref}^2}{R_{bc}V_{fc}} \quad (25)$$

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

$$s = x_1 - x_{1bc}^* \quad (26)$$

The control (u) designed to achieve sliding (enforcing x_1 to track x_{1bc}^*) is:

$$u = \left(\frac{1}{2} \right) [1 - \text{sign}(s)] \quad (27)$$

The equivalent control (U_{eq}) is obtained by solving:

$$\dot{s} = 0 \quad (28)$$

$$U_{eq} = 1 - \frac{V_{fc}}{x_2} \quad (29)$$

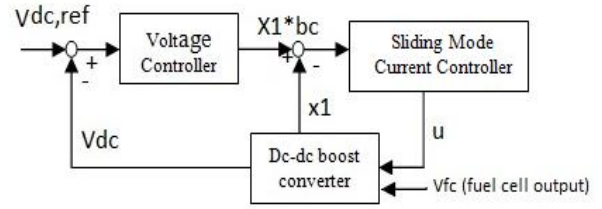


Figure 2. SMC control strategy

B. Inverter Modeling and Control

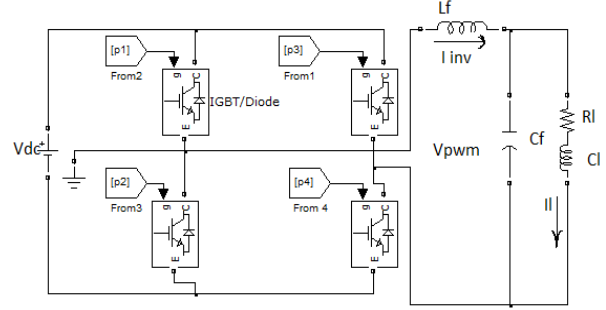


Figure 3. Simulink model of single phase full bridge inverter

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

$$\dot{x}_p = Ax_p + Bu \quad (30)$$

$$y = Cx_p + Du \quad (31)$$

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 system matrices are as:

$$A = \begin{bmatrix} 0 & \frac{1}{C_f} & -\frac{1}{C_f} \\ -\frac{1}{L_f} & 0 & 0 \\ \frac{1}{L_l} & 0 & -\frac{R_l}{L_l} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \frac{1}{L_f} \\ 0 \end{bmatrix} \quad x_p = \begin{bmatrix} V_c \\ I_{inv} \\ I_l \end{bmatrix} \quad (32)$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad u = [V_{pwm}] \quad D = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad (33)$$

IV. SIMULATIONS AND RESULTS

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.

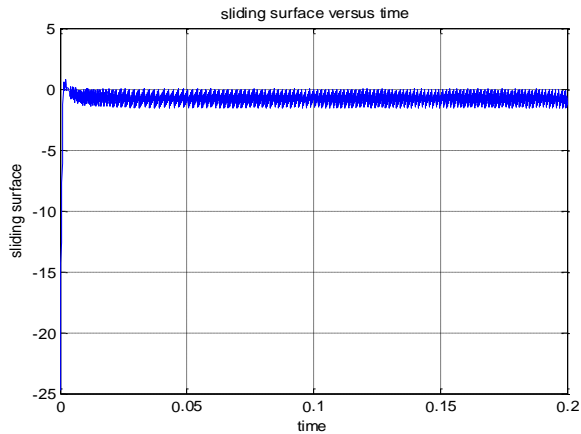


Figure 4. Sliding Surface $s=0$

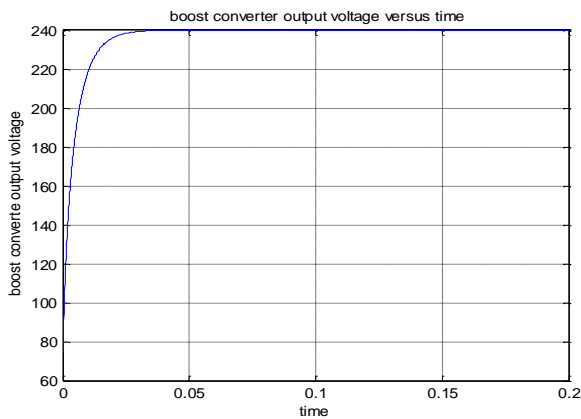


Figure 5. Output voltage of Dc-Dc boost converter

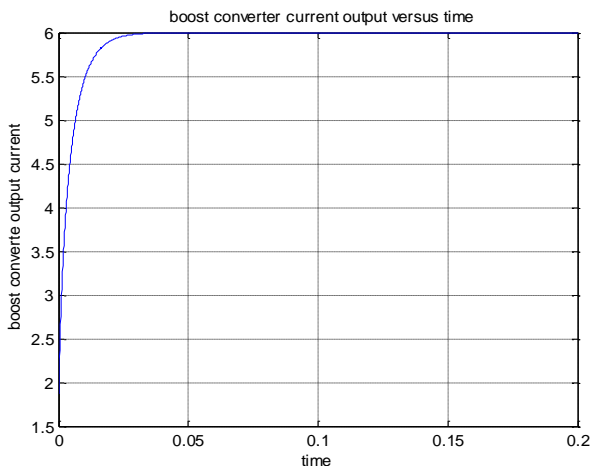


Figure 6. DC Output current

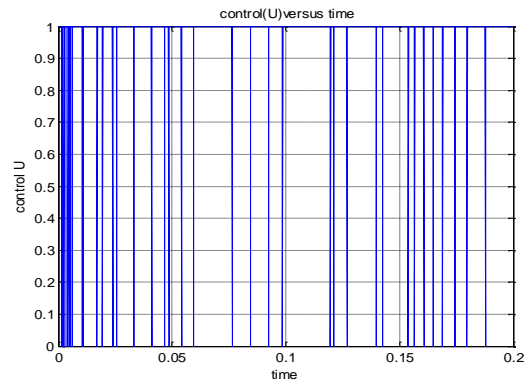


Figure 7. Control switching pattern

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.

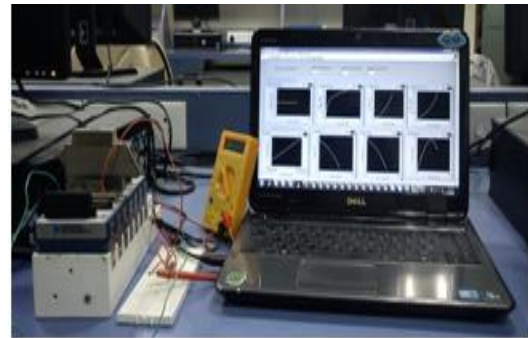


Figure 8. Experimental setup

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

(MEA). 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.

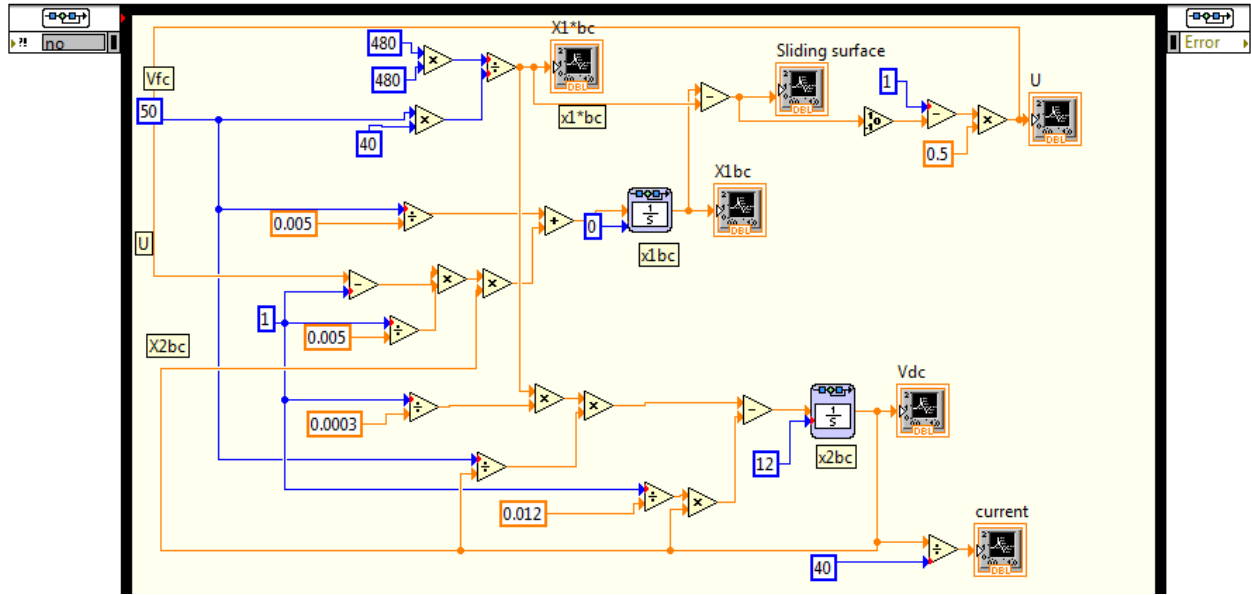


Figure 9. Labview back panel of SMC

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

Parameters	Symbol	Value
Inverter inductor	L_f	25 mH
Inverter capacitor	C_f	100 μF
Inverter frequency	f	60Hz
Inverter input	V_{dc}	300V
Load inductance	L_l	15 mH
Load resistance	R_l	5.55 Ω
Standard voltage	E_{cell}^0	1.23V
Activation loss constants	a_0 a b	1.3697V -0.00308 9.724×10^{-5}
Ohmic loss constants	R_{oc} K_T K_I	0.0033 Ω $-7.5 \times 10^{-6} \Omega/K$ $7.85 \times 10^{-4} \Omega/A$
Limiting current	I_l	0.0333 A
Convective heat transfer coefficient	h_s	37.5 W/($m^2 K$)
Area of single cell	A_s	0.032 m^2
Specific heat capacity	C_{fc}	500 J/(molK)

Parameters	Symbol	Value
Mass of fuel cell	M_{fc}	44 Kg
Flow delay at anode	λ_a	60 sec
Flow delay at cathode	λ_c	
Anode,Cathode channel pressure	U_{pa}, U_{pc}	-
Ambient temperature	U_{Tr}	-
Partial pressure of x	P_x	-
Net molar flow rate of x	$(mx)_{net}$	-

ACKNOWLEDGMENT

I would like to thank the scientists of NCL Pune for their guidance and support in hardware fabrication and experimentation. I would also like to acknowledge Mr. Sachin Puranik's help in state-space modeling.

REFERENCES

- [1] C. Wang, M. H. Nehrir, and S. R. Shaw, "Dynamic models and model validation for PEM fuel cells using electrical circuits," *IEEE Trans. Energy Conversion*, vol. 20, no. 2, pp. 442–451, June 2005.
- [2] S. V. Puranik, A. Keyhani, and F. Khorrami, "State-space modeling of proton exchange membrane fuel cell," *IEEE Trans. Energy Conversion*, vol. 25, no. 3, Sept. 2010.
- [3] C. Wang, M. H. Nehrir, and H. Gao, "Control of PEM fuel cell distributed generation systems," *IEEE Trans. Energy Conversion*, vol. 21, no. 2, pp. 586–595, June 2006.
- [4] L. Y. Chiu, B. Diong, and R. S. Gemmen, "An improved small-signal model of the dynamic behavior of PEM fuel cells," *IEEE Trans. Ind. Appl.*, vol. 40, no. 4, pp. 970–977, July/Aug. 2004.
- [5] F. Musio, F. Tacchi, L. Omati, P. G. Tampino, G. Dotelli, S. Limonta, D. Brivio, and P. Grassini, "PEMFC system simulation in Matlab-Simulink," Science Direct, Hydrogen Energy.
- [6] J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, "Control of fuel cell breathing," *IEEE Control Syst. Mag.*, vol. 24, no. 2, pp. 30–46, Apr. 2004.

- [7] V. Utkin, J. Guldner, and J. X. Shi, "Sliding mode control in electromechanical systems," London, U.K.: Taylor and Francis, 1999.
- [8] F. Khorrami, S. puranik, A. Keyhani, P. Kishnamurthy, and Y. She, "PEM fuel cell distributed generation system modeling and robust non-linear control."



Bharti Kumari belongs to Mumbai (India). She graduated in Bachelors of Engineering, Instrumentation and Control discipline from Pune University in 2010 and then completed her Masters in Process Instrumentation from College of Engineering Pune, India in 2012. As a student she has worked on fuel cell for Master's Thesis from her college, in association with NCL Pune. Her research interests include fuel cell and its control.



Ravindra S. Rana belongs to Mehsana, Gujrat (India). He graduated in Bachelors of Engineering, Instrumentation and Control discipline from Gujrat University in 2010 and then completed his Masters in Process Instrumentation from College of Engineering Pune, India in 2012. As a student he has worked in digital control systems. His research interest includes design of advanced controllers and Observer-controller combinations for uncertain systems.