HIGHER-ORDER SLIDING MODE OBSERVER-BASED FAULT DIAGNOSIS IN POLYMER ELECTROLYTE MEMBRANE FUEL CELL SYSTEM

by

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DOCTOR OF PHILOSHPY (PhD) IN ELECTRONIC ENGINEERING

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Dedicated to my parents and family

CERTIFICATE OF APPROVAL

It is certified that the research work titled “higher-order sliding mode observer-based fault diagnosis in polymer electrolyte membrane fuel cell system,” carried out by Syed Ijaz Hussain Kazmi, Reg.No.PE073001, under the supervision of Dr. Muhammad Aamer Iqbal Bhatti, at Mohammad Ali Jinnah University, Islamabad Campus. It is fully adequate, in scope and in quality, as a synopsis for the degree of PhD of Electronic Engineering.

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I do not forget the marvelous cooperation and support from my family all over the period of studies. One is doing prayers for my success all the times day and night, she is my mother. I believe that she shall listen soon to good news Inshaa Allah.

DECLARATION

It is declared that this is an original piece of my own work, except where otherwise acknowledged in text and references. This work has not been submitted in any form for another degree or diploma at any university or other institution for tertiary education and shall not be submitted by me in future for obtaining any degree from this or any other University or Institution.

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ABSTRACT

This synopsis is about higher-order sliding mode observer-based fault diagnosis in polymer electrolyte membrane (PEM) fuel cell system. The PEM fuel cell systems have a potential to reduce pollutant emissions and dependence on fossil fuels as they consume hydrogen gas as a fuel and their major byproduct is portable water. They are promising candidate for automotive propulsion source due to their special characteristics of fast start-ups, light weight, low operating temperature and high power densities. In the last decade, control community has made great deal of efforts to enhance performance, effective monitoring and increase in durability of the system.

A robust controller can enhance performance even in the presence of model incompetence, external disturbances and uncertainties. Immeasurable or difficult to measure model parameter can be estimated using model based observers. The observation can made health monitoring of the system possible. Fault diagnosis in the system preventing the system from entering faulty modes, can ensure the reliability and durability of the system.

The higher order sliding mode technique is robust, fast convergent and chattering free technique. The robustness property of this technique can enable to detect faults on the basis of parameter estimation even in the presence of disturbances and uncertainties. Higher-order sliding mode observer, having property of unknown input, exhibited accurate parameter estimation that made this technique effective in low current densities and even in the no load conditions. There is no technique effective in such scenarios so far. Therefore the proposed technique would be a worthy contribution to the research.

The critical parameters are estimated using higher order sliding mode observers that include oxidizer mass flow rate and water content across the membrane of PEM fuel cell system. The results were verified by comparing with international bench model of PEM fuel cell system. The designed higher order sliding mode observers will be used for fault diagnosis in PEM fuel cell system. The fuel cell system is prone to faults i.e. water flooding and dehydration of membrane. The manifold leakage of hydrogen and oxygen result in fuel and oxygen starvation in the stack ultimately. The hydrogen leak is potentially dangerous fault also. Therefore the synopsis converges to do fault diagnosis in PEM fuel cell system using higher order sliding mode observers.

LIST OF PUBLICATIONS

Published Papers

1. **Kazmi I. H**., Bhatti A.I., Iqbal M., “Parameter Estimation of PEMFC system with Unknown Input,” IEEE Proceedings of 2010 11th International workshop on variable structure systems, VSS 2010, pp. 301-306, Mexico city, Mexico.
2. **Kazmi I. H**., Bhatti A. I., Iqbal S., “A Nonlinear observer for PEM fuel cell system,” IEEE proceedings of INMIC 2010, Islamabad.
3. **Kazmi I. H**., Bhatti A. I., Iqbal M., “Nonlinear Observer for PEM fuel cell system using super twisting algorithm,” Proceedings of 7th IBCAST 2010, pp. 128-133, 2010, Islamabad.
4. Ahmed Q., Bhatti A. I., Iqbal S., **Kazmi I. H**.,"2-sliding mode based robust control for 2-DOF helicopter," Proceedings of VSS 2010, pp. 481-486 , Mexico city, Mexico.
5. Iqbal M., Bhatti A. I., **Kazmi I. H**., khan Q., “Second order sliding mode observer design for nonlinear systems, ”proceedings of 7th IBCAST 2010, pp. 123-127, 2010, Islamabad.
6. **Kazmi I. H**., Bhatti A. I. “Robust controller using LMI framework for PEM fuel cell system,” IEEE Proceedings of 2009 International conference on emerging technologies, ICET 2009, pp. 136-141, Islamabad.
7. Iqbal M., Bhatti A.I., Iqbal S., Khan Q., **Kazmi I. H**., "Parameter estimation of uncertain nonlinear MIMO three tank systems using higher order sliding modes," Proceedings of IEEE International Conference on Control and Automation (ICCA 2009), pp. 1931-1936, Christchurch, NZ.
8. Iqbal M., Bhatti A. I., Iqbal S., Khan Q., **Kazmi I. H**., "Fault diagnosis of nonlinear systems using higher order sliding mode technique," Proceeding of 7th Asian Control Conference, ASCC 2009, pp. 875-880, Hong Kong.
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TABLE OF CONTENTS

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

FCS	Fuel Cell System
PEM	Polymer Electrolyte Membrane
PAFC	Phosphoric Acid Fuel Cell
AFC	Alkaline Fuel Cell
MCFC	Molton Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell

SMO	Sliding Mode Observer
FOSMO	First Order Sliding Mode Observer
HOSMO	Higher Order Sliding Mode Observer

Chapter 1

INTRODUCTION

The last two centuries were ruled by steam and internal combustion engines respectively but the 21st century is regarded to be dominated by fuel cell engine in the field of power generation for a variety of applications. The fuel cell technology has passed the demonstration stage and entered the commercialization phase through recent developments. Fuel cell technology has a wide variety of power applications ranges from portable computer to transportation and large scale buildings. The Polymer Electrolyte Membrane (PEM) fuel cell technology is most promising for automotive applications due to efficient source of power along with its special characteristics as fast start-ups, light weight, low operating temperature and high power densities. Despite these impressive advantages, the PEM fuel cell systems are prone to faults generally as other engineering systems but also due to its multidisciplinary and complex nature, it is highly prone to faulty modes. The fault diagnosis can prevent the system to enter the faulty modes.

1.1 Overview

Fault diagnosis, preventing the system from entering faulty modes, can ensure the performance, reliability and durability of the system. The durability of the PEM fuel cell system is hot issue and different researchers are working in it. Major type of degradation of the PEM fuel cell system is caused by faulty operation modes of the system. The starvation of reactant gases, dehydration of membrane and flooding of electrodes. The health monitoring can be done via observation of mass flow rates of reactant gases and water dynamics of the system.

The smooth operation of system hinders by different faults. The faults include sensor, actuator, and system faults. The temperature, pressure, humidity and mass flow rate sensors are incorporated in the fuel cell system. The pump, blower and compressor are actuators. The system faults include starvation of reactant gases, flooding and dryness scenarios etc. The prevention from entering faulty modes, the performance, reliability and durability of the system can be enhanced. If system fault occurs due to complexity of physical processes and functional limitation of components then the fault tolerant strategy can prevent the system from failure and can reinstate the system to smooth operation.

1.2 Problem Statement

Mathematical models whatsoever their purpose for development, play a vital role in the understanding of system behaviors under different operating conditions. There is a dire need of mathematical model to understand the insight of the processes. The comprehensive model can support fault diagnostics and control to prevent from continuous degradation. The dynamic mathematical model is multipurpose achievement that leads to model based parameter estimation, state observation and fault diagnosis. The model based fault tolerant control can be designed eventually.

The monitoring of fuel cell operation needs understanding and knowledge of different parameters. The parameters of interest are required to be observed for monitoring and then to ensure the smooth operation of fuel cell system.

The estimated parameter can provide source for fault diagnosis of PEM fuel cell system. The mass flow rate of air and hydrogen may be helpful in the diagnosis of starvation and leakage of reactant gases. Especially in the case of hydrogen, leakage is a dangerous fault. The estimation of water content parameter is helpful to detect flooding and drying scenarios of PEM fuel cell system. The drying mode drastically damages the membrane whereas flooding mode degrades the performance substantially.

1.3 Applications of the Research

The proposed scheme of fault diagnosis will be robust and fast convergent. The higher order sliding mode observer based technique will work despite uncertainties and disturbances. This technique, having property of unknown input, will be effective in low current densities and even in the no load conditions. There is no technique effective in such scenarios so far. Therefore the proposed technique would be a worthy contribution to the research.

1.4 Synopsis Organization

The synopsis consists of six chapters. In the first chapter, introduction of proposal and salient feature are discussed. Second chapter describes PEM fuel cell system in detail. The explanation encompasses component to system including cell, stack and system. The dynamics of system are also discussed. Three systems are explained including small, medium and automotive level. Third chapter presents comprehensive and detailed literature review for control oriented dynamical model of fuel cell system. The literature review contains model based observers as well. The fault diagnosis in PEM fuel cell system is discussed. A glimpse of faults is included in the section. The fourth and fifth chapters contains application of higher order sliding mode technique for estimation of mass flow rate and water content across the membrane of fuel cell system. In the last chapter, future work and its time line is given.

1.5 Summary

In this chapter, brief overview on fault diagnosis, problem statement, and research motivation along with research objectives is discussed. Synopsis organization is also briefly discussed. It would be better to proceed further after a good understanding of insights of PEM fuel cell system.

Chapter 2

FUEL CELL SYSTEM

The fuel cell technology has passed the demonstration stage and entered the commercialization phase through recent developments. Fuel cell technology has a wide variety of power applications ranges from portable computer to transportation and large scale buildings. Despite this impressive scenario, there are still many problems and challenges for this technology to be a commercial automotive propulsion source. The challenges include high cost, rival technology, water management, cooling, and hydrogen supply. In this chapter, fuel cell system is discussed in detail. The chapter describes and focuses the most suitable fuel cell system for automotive applications. The advantages and issues are also discussed. A glimpse is presented on control oriented solutions.

2.1. Working Principle of Fuel Cell

Fuel cell is an electrochemical device that converts chemical energy of fuel into electricity. It has layered structure having electrolyte sandwiched by electrically electrodes. Two chemical processes namely oxidation of fuel at anode and reduction of oxidant at cathode cause a potential difference. This potential difference is exploited using an external circuit for electric current. The fuel cells work on the principle irrespective of their type.

2.2. Fuel Cell Types

Fuel cell types are basically originated due to fundamental problems of slow chemical reaction rate and non-availability of ready hydrogen fuel although fuel cell was evolved from reverse electrolysis with an input of hydrogen as shown in Figure 2.1. The classification of fuel cells is appeared in the literature on different criteria. The criteria include: nature of electrolyte, temperature range, method of fueling, type of fuel and application area. The electrolytes include polymer membrane, phosphoric acid, molten carbonate, alkaline and solid oxide. The aqueous, molten and solid electrolytes are used in low, intermediate and high temperature fuel cells respectively. The upper limits of temperature ranges are 100^0C, 500^0C, 1000^0C and beyond of 1000^0C as low, medium high and very high temperature respectively. The fueling methods include direct, indirect and regenerative schemes. In the direct method, the products of cell reaction are discarded whereas in the indirect method, fuel is reformed. In the regenerative method, the products are subjected to regenerate the spent products through thermal or electrical technique. The types of fuel are hydrogen ethanol, and methanol etc. The application area ranges from portable devices to automobiles and buildings having power generation of single watt to multiple of mega watts. The major types of fuel cells are alkaline fuel cell (AFC), polymer electrolyte membrane (PEM) fuel cell, phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), and molten carbonate fuel cell (MCFC).

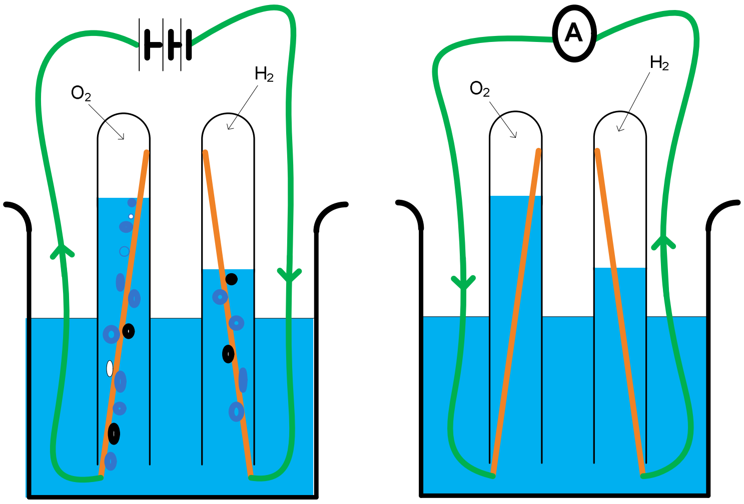


Figure 2.1.Comparison of Electrolysis and Fuel Cell Principle

(Larminie and Dicks, 2003)

In fuel cell reaction, electrode and electrolyte are not consumed but fuel and oxidant are consumed. Some other cells are reported in the literature as fuel cell but they do not comply with basic definition of fuel cell i.e. an electrochemical device. They may consume electrolyte or electrode in their process. The cells include biological cell, metal/air cell and redox flow cell or regenerative fuel cell. The chemical reactions in different fuel cells are shown in Table 2.1 (Larminie and Dicks, 2003).

Table 2.1 Typical Electrochemical Reaction in Fuel Cells

Type	Electrolyte	Mobile Ion	Anode Reaction	Cathode Reaction
PEM	Nafion / Dow	H^+	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
PAFC	Concentrated phosphoric acid	H^+	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
AFC	35-50% KOH	OH^-	$H_2 + 2(OH)^- \rightarrow 2\ H_2O + 2e^-$	$1/2O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
MCFC	Na2CO$_3$ / Li2CO3	CO_3^{2-}	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$1/2O_2 + CO_2 + 2e^- \rightarrow 2CO_3^{2-}$
SOFC	ZrO_2 / Y_2O_3	O^{2-}	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$1/2O_2 + 2e^- \rightarrow O^{2-}$

The fuel cells are hydrogen fueled. The moving ions are different in different fuel cells. The details of electrolyte are also given in the Table 2.1.

In the above discussion, the major fuel cells are explained in detail. In the current job, PEM fuel cell will be focused due to its specific characteristics suitable for automotive application. In automotive industry, batteries and combustion engines are used separately or in hybrid fashion. Therefore as a black box, the comparison among these systems is presented as shown in Figure 2.2.

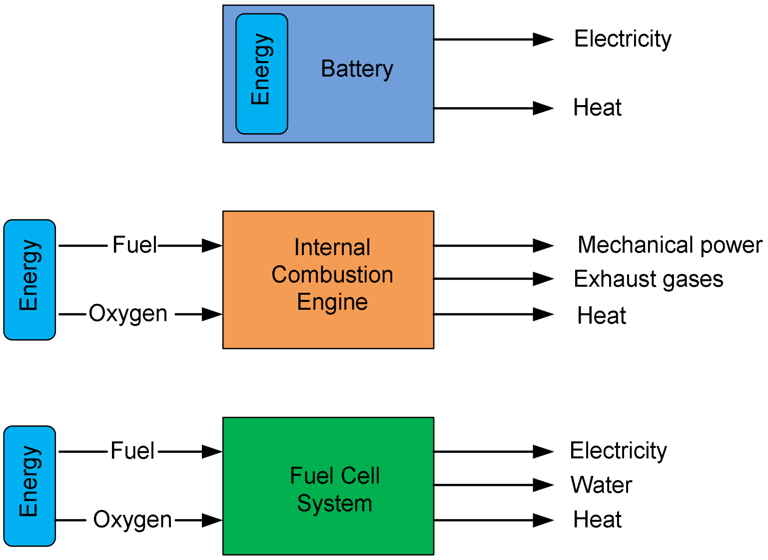


Figure2. 2 Comparisons among Battery, Combustion Engine and Fuel Cell Engine

The fuel cells are different from batteries on the basis of continuous feeding of reactants and are different from internal combustion (IC) engines on the basis of outputs. The fuel cell converts chemical energy directly to electricity. The combustion engines convert chemical energy into thermal then mechanical and finally electricity. The batteries are basically energy storage devices. They do not generate energy themselves but from another sources energy is stored in the batteries and later the sorted energy is utilized. The later part of the report will focus PEM fuel cell and its structure and stack. Finally PEM fuel cell system of different sizes will be discussed form portable to automotive applications.

2.3. PEM Fuel Cell Structure

The PEM fuel cell has layered structure as shown in Figure 2.3. The fuel cell is a unit block of fuel cell stack is and it consists of Membrane Electrode Assembly (MEA) sandwiched with cathode and anode. The anode and cathode can be identified by the direction of flow of electrons. If the flow direction of the electrons is towards an electrode then it is called cathode and in the case of anode it is vice versa. This identification holds true for fuel cells as well as other devices e.g. diodes etc. The MEA contains a membrane and electrode on its both sides.

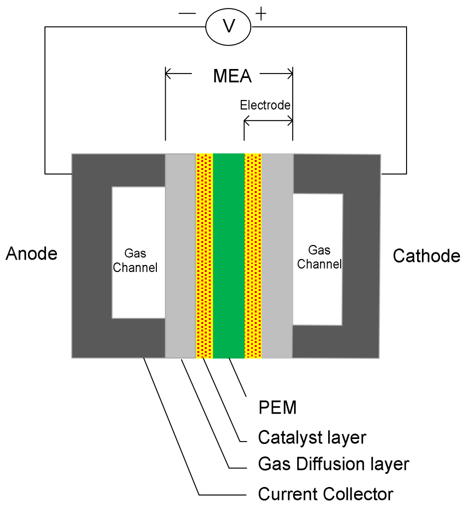


Figure 2.3. Schematic of PEM Fuel Cell

The membrane separates the reduction and oxidation half reactions. It allows the protons to pass through to complete the overall reaction while forcing the electrons to an external circuit. The electrode consists of Gas Diffusion Layer (GDL) and Catalyst Layer (CL) in MEA. At the both ends there are end plates which act as current collector in a single fuel cell as shown in Figure 2.3.

Gas diffusion layer is a part of electrode and has multiple functions due to its materials and structure. It forms an electrical connection between the carbon-supported catalyst and the bipolar plate. It provides channels for flow of reactant gases. It provides a protective layer over the very thin layer of catalyst. It carries the product water away from the electrolyte surface. The catalyst layer stimulates each half reaction. The details of MEA materials and its manufacturing alternatives can be seen in the literature (Mehta and Cooper, 2003). The different electrode designs can be studied in the review (Litster, 2004). The schematic of MEA is shown in Figure 2.4.

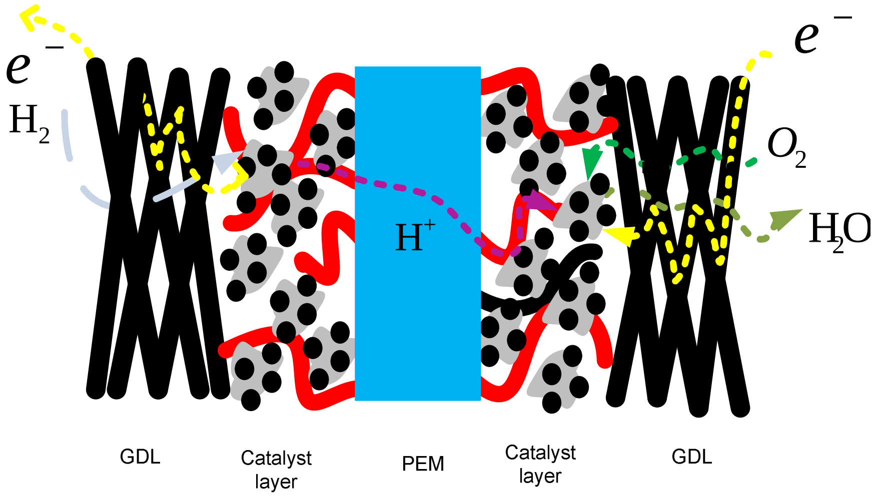


Figure 2.4. Schematic of Membrane Electrode Assembly (MEA)

The reactants flow through pores present in GDL and reach to catalyst layer. The generated electrons travel through electrically conductive fibers present in GDL and collects at conducting electrode of anode. Due to difference of electric potential, these electrons flow through external circuit to cathode. Hydrogen ions go across the membrane from anode catalyst to cathode catalyst. The membrane is ion conductor whereas in the catalyst, they travel through proton conducting media. The hydrogen ions, electrons and oxygen react mutually at cathode. The water is generated. The some part of water diffuses through membrane to anode due to water gradient from cathode to anode while hydrogen ions carry water droplets form anode to cathode under Osmo-electric drag.

2.4. Fuel Cell Stack

Fuel cell stack has many fuel cells because single fuel cell has output voltage up to single volt which is not sufficient for any application. For automotive applications there is a need of power in kilowatts therefore fuel cells are connected in series together for desired voltage. There is a bipolar plate in-between each pair of MEAs i.e. the plate is sandwiched by MEAs. It means that it has contacts with cathode and anode simultaneously. Bipolar plate separates the individual cells in the stack. Its basic function is to carry current away from the cell. It distributes the reactant gases and facilitates water management within the cell. In the absence of dedicated cooling plates, it also helps in heat management.

The MEA looks similar, works in the same way and needs similar care in use irrespective of manufacturer and its method of manufacturing i.e. rolling, printing, sputtering and spraying but fuel cell stacking varies very much.

The reactant gases are supplied to the fuel cell stack for electrochemical reactions through two types of manifolds namely open-end and dead-end manifolds. The former type of manifolds is employed for cathode as well as anode but latter type can be incorporated only for anode in order to avoid hydrogen waste. The open-end manifold for anode is related to recirculation of hydrogen supply. In this process hydrogen at exhaust of anode is sent back to the inlet of the anode through an appropriate device. Hydrogen may be in pure form or reformed shape containing other gases as well. Recirculation method is adapted in the case of pure hydrogen otherwise it decreases the hydrogen concentration at anode due to presence of other gases. Good anode recirculation can humidify the fresh hydrogen with the anode outlet mixture and obtain good water management by running the hydrogen mixture. The recirculation process can be done with an active or passive device. The active devices are pump and compressors whereas ejector is called passive device. The screw compressor is an active device and has a wide operations zone of high efficiency and is insensitive to the presence of liquid water. This kind of air system is widely used in the current application.

2.5. Fuel Cell System

The fuel cell system consists of fuel cell stack and auxiliary systems. The core part of the system is the fuel cell stack. Its components are membranes, catalysts, gas diffusion layers, bipolar and end plates. The auxiliary systems are air supply system, fuel supply system, humidification system, cooling system and power conditioning system. Three systems of small, medium and automotive level are discussed in the following lines. Their schematics are shown as in Figure 2.5, Figure 2.6 and Figure 2.7 respectively. In the schematics, it is assumed that pure hydrogen is available for supply. Therefore reforming system for hydrogen supply is not shown in the diagrams.

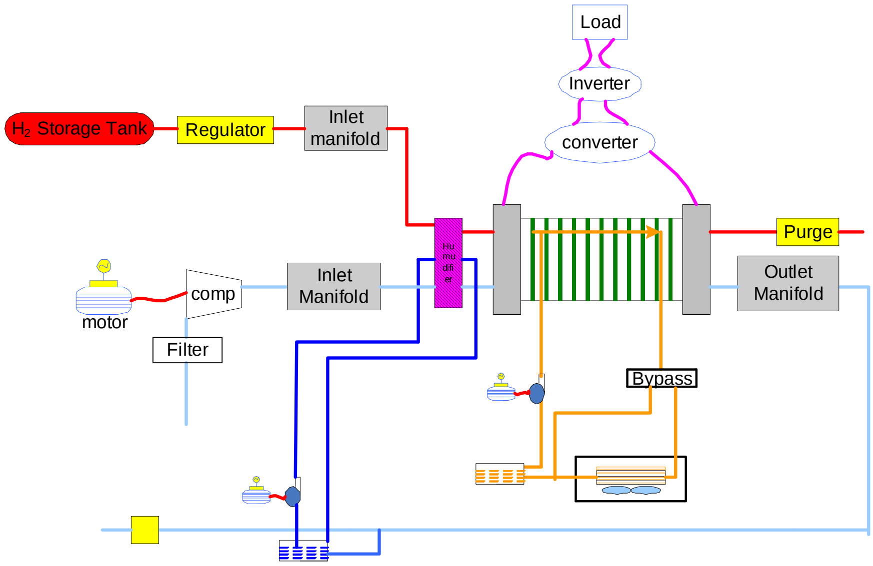


Figure 2.5: Schematic Diagram of Automotive Fuel Cell System

Automotive fuel cell system schematic is shown in Figure 2.5. The air supply system comprises of electric motor, air compressor and manifolds whereas fuel supply system has fuel storage cylinder and regulating valves etc. The humidification system consists of pump and valves etc. The coolant system contains radiator, pump, manifold, valves and reservoir. The power conditioning system contains converter and inverter.

Medium size fuel cell system is Nexa power module. The module can be integrated with light vehicles for example golf cart etc. A schematic of Nexa power module is shown in Figure 2.6. The diagram shows interfaces air supply, through humidity exchanger, hydrogen supply, cooling system with fuel cell stack. The green lines show the air supply system whereas red line shows the hydrogen supply loop. In the system there is a controller for monitoring of performance and ensures safety of the fuel cell stack via generating alarm and then shut down the system during unsafe operating condition. It regulates hydrogen supply too. The air supply is also regulated as per demand of load current. At high load current, more air is supplied through compressor. The system is air cooled through a fan. The operating temperature of fuel cell stack is controlled via modulating the fan speed. The measured variables for controller feedback are also shown in schematic diagram.

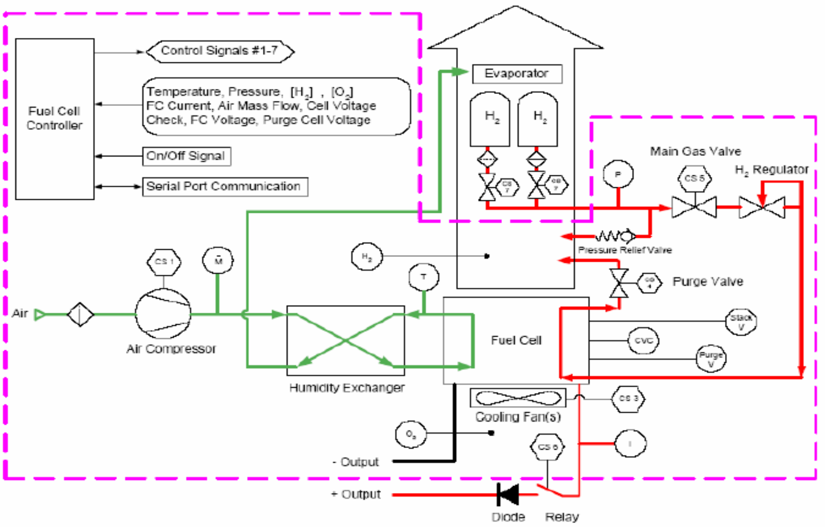


Figure 2.6: Schematic Diagram of Nexa Fuel Cell System

The many researchers worked on Nexa fuel cell system. Shevock (2008) developed a system level model and validated on the Nexa fuel cell system. Choi (2004) developed an equivalent electrical circuit of the system. Ottesen (2004) worked on dynamic performance of the module.

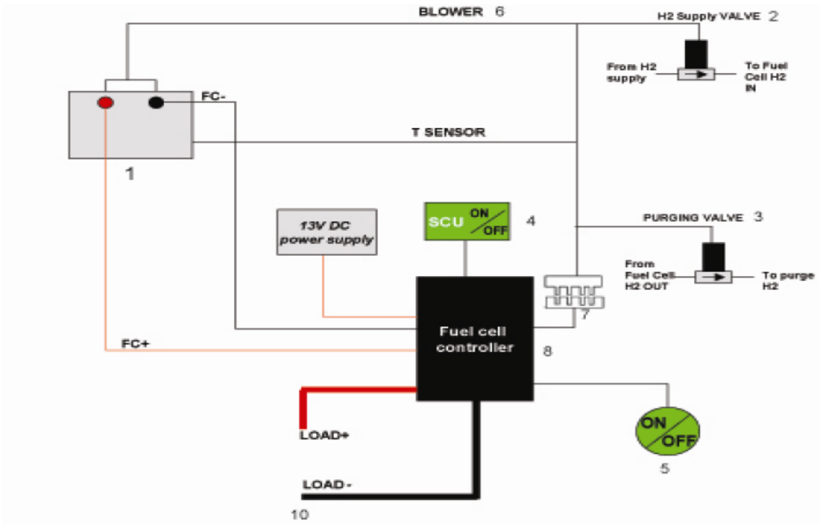


Figure 2.7: Schematic Diagram of H-100 Fuel Cell System

A portable fuel cell system was purchased by Mohammad Ali Jinnah University, Islamabad. The system diagram is shown in Figure 2.7. The fuel cell stack (1), hydrogen supply valve (2), purge valve (3), short circuit unit (4), on/off switch (5), blower (6), controller connecter (7), controller (8) and load connectors (10) are shown in system diagram. The controller prevents damage of fuel cell stack only.

Table 2.2 Parameters of PEM fuel cell systems

Parameter	Type of System		
	Portable	Medium	Automotive
Number of cells	24	43	381
Power	100 W	1200 W	75kW
Stack Temperature	65 C	65 C	80 C
Humidification	Self-humidified	Humidity exchanger	Humidifier
Cooling	Fan (air cooled)	Fan (air cooled)	De-ionized water
Oxidant supply	Open cathode	compressor	Compressor
Weight	950 grams	12250 grams	250kg
Dimensions	15x10.9x9.4 cm	56x25x33 cm	145x87x49 cm
Controller	yes	yes	yes

A comparison of three systems, discussed above is shown in Table 2.2. All systems required pressurized hydrogen supply and then regulator is required to maintain the pressure of hydrogen as per system requirement. The oxygen is supplied through air. For small scale system, a fan is sufficient for air supply but medium and automotive scale system, the compressed air is necessary for power generation. The system parameters are taken from user manuals (Horizon fuel cell technologies, 2008, Heliocentris Nexa Power Module, 2009) and research paper by Pukrushpan *et al*. (2004).

2.6. Applications

Fuel cell applications have a variety of large range because fuel cell system can give power from single watt to many megawatts. But basically the application is dependent to type of a fuel cell. Each type has its own distinguishing characteristics. On smaller scale, fuel cells can be used in cell phones, playing toys, personal computers and other personal electronic devices. In the medium range, it can be used in automotive industry and indoor applications. On the larger scale, the fuel cell can be used for residential buildings and distributed power grids. Therefore major classification applications include portable fuel cell, transportation and stationary applications.

Table 2.3 Major type of fuel cells

(Kordesch and Simader, 1996, Larminie and Dicks, 2003)

Fuel cell type	Operating temperature	Efficiency (cell)	Power range Watts	Typical Applications
PEM	30-100^0 C	50-60%	1-100k	Vehicles and mobile applications
PAFC	160-220^{0}C	55%	10K-1M	200 kW CHP
AFC	60-90^{0}C	50-60%	1k-10k	Space vehicles e.g. Apollo, Shuttle
MCFC	~650^0 C	60-65%	1M-10M	Power generation MW CHP
SOFC	500-1000^0 C	55-65%	1k-10M	Power generation 2kW to MW CHP

The details of different applications of fuel cell e.g. unmanned under water vehicle, submarines, locomotives, surface ships, buses and automobiles can be seen in the literature (Amphlett *et al.*, 1995). One can find the details of the Polymer Electrolyte

Membrane (PEM) fuel cell applications in detail in the review (Wee *et al.*, 2007). Many companies working on fuel cell technology (Ballard, UTC, Nuvera, GE-FCS, Plug Power, Intelligent Energy, NovArs, Smart fuel cell, Toshiba, Sanyo and Hydorgenics etc.) and automobile (Daimler-Chrysler, Ford, Renault, Toyota, Nissan, GM, BMW and Hyundai etc.) have announced various applications.

2.7. Advantages and Issues

Fuel cell technology offers many advantages on other energy converters. The advantages include high efficiency and strong reliability, environment friendliness, unique operating characteristics, planning flexibility and future development potential (Kordesch and Simader, 1996).

Efficiency of fuel cell is generally greater than conventional energy converters e.g. combustion engines whether piston based or turbine. The efficiency depends upon type of fuel cell. Different fuel cells present different efficiencies in the range of 55 to 65% whereas in the lab experiments up to 90% efficiency is reported. The reliability of fuel cell is obvious significantly due to its simplicity as there is no moving part in the stack core part of the system and fewer moving parts in overall system. Moreover the gradual degradation ensures reliability because there is no catastrophic failure as can occur in combustion engines.

Environment friendliness is unparallel characteristic of fuel cell technology due to low emission of pollutants. The conventional power generators produce sulfur oxides and nitrogen oxides which harm the environment. The hydrogen fuel cells produce portable water as a byproduct of main chemical reaction. Moreover the fuel cell operation is silent due to its electrochemical nature therefore the noise is absent in the case of fuel cells. Other all combustion based power generator pollute the environment with noise and harmful byproducts.

The fuel cell offer beneficial operating characteristics. These characteristics save cost in meeting system operating conditions. The operating benefits include load following, power factor correction, quick response to power generating unit outages, control of distribution line voltage and quality control.

The performance does not depend upon the size of fuel cell plant. As per requirement the system can be incremented by adding small units. Therefore the fuel cell technology provides flexible planning.

Fuel cell has a great future potential for development. Other technologies are almost at matured stage of development therefore a small incremental improvement can be done whereas fuel cell technology is in a developing phase.

Despite these impressive advantages, there are still many problems and challenges for this technology to be commercially automotive propulsion source. The challenges include high cost, rival technology, water management, cooling, and hydrogen supply (Larminie and Lowry, 2003). The fuel cells are quite difficult system to manufacture due to large complex parts and then their very careful assembly those result in expensive systems. The combustion engines are also subject to hydrogen fueling and mitigating pollutants and enhancing efficiency. The fuel cell does not work under flooding and drying scenario. Therefore water management is required. The water management is not easy job. It is a complex job and has coupled problem. The self hydrated polymer membrane is manufactured but it makes the membrane more complex and costly. In the flooded cathode, the compressed air is blown over the cathode but it increases parasitic load. Moreover in the case of compression, the temperature of air rises and introduces other difficulties. In the case of drying scenario, humidification is required. The humidification equipment increases the system size, complexity and cost. The cooling of fuel cells are difficult than IC engines. The PEM fuel cell has low temperature characteristics, therefore heat dissipation in the environment is not sufficient as comparing to IC engines. The hydrogen is not ready available in the environment. The hydrogen is produced from other chemical compounds.

2.8. Control Oriented Solutions

The PEM fuel cell system poses many control problems. The problems include output voltage stabilization, prevention from oxygen and fuel starvation, maintenance of equal partial pressure in anode and cathode, water and thermal management. The solution of these technical issues maximizes the performance and life of the system simultaneously.

In the accomplishment of control task, there are some obstacles. Many variables of fuel cell system are not measureable or difficult to measure for example partial pressures of oxygen and hydrogen in cathode and anode. Prior to devise control strategy, the effective monitoring of the system is essential. The monitoring of fuel cell operation needs understanding and knowledge of different parameters. The parameters of interest are required to be observed for monitoring and then to ensure the smooth operation of fuel cell system.

The smooth operation of system hinders by different faults. The faults include sensor, actuator, and system faults. The temperature, pressure, humidity and mass flow rate sensors are incorporated in the fuel cell system. The pump, blower and compressor are actuators. The system faults include starvation of reactant gases, flooding and dryness scenarios etc. The prevention from entering faulty modes, the performance, reliability and durability of the system can be enhanced. If system fault occurs due to complexity of physical processes and functional limitation of components then the fault tolerant strategy can prevent the system from failure and can reinstate the system to smooth operation.

The estimated parameter can provide source for fault diagnosis of PEM fuel cell system. The mass flow rate of air and hydrogen may be helpful in the diagnosis of starvation and leakage of reactant gases. Especially in the case of hydrogen, leakage is a dangerous fault. The estimation of water content parameter is helpful to detect flooding and drying scenarios of PEM fuel cell system. The drying mode drastically damages the membrane whereas flooding mode degrades the performance substantially.

2.9. Summary

The Polymer Electrolyte Membrane (PEM) fuel cell technology is most promising for automotive applications due to efficient source of power along with its special characteristics as fast start-ups, low weight, low operating temperature and high power densities. There are still many challenges for this technology to be commercial automobile. The water management and thermal management are key issues in its way to be reality as automotive system at commercial level. To overcome the problems, there is a dire need of mathematical model to understand the insight of the processes. The comprehensive model can support fault diagnostics and control to prevent from continuous degradation. The dynamic mathematical model is multipurpose achievement that leads to model based parameter estimation, state observation and fault diagnosis. The model based fault tolerant control can be designed eventually.

Chapter 3

LITERATURE SURVERY

This chapter presents a detailed literature survey for suitable control oriented dynamical mathematical model for automotive application. The discussion encompasses empirical models to first principal based models. Secondly, model based techniques are discussed for observation and control purposes. Fault diagnosis in PEM fuel cell system is discussed with a glimpse of system faults. Actually polymer electrolyte membrane fuel cell system is highly nonlinear and uncertain system therefore the robust nonlinear technique merits for parameter observation and control of the system.

3.1. Mathematical Models of Fuel Cells

Mathematical models whatsoever their purpose for development, play a vital role in understanding the system behaviors under different operating conditions. The models generally can be categorized as theoretical or semi-empirical on the basis of approaches employed for their development. The state of model can differentiate its nature either steady state or transient. The boundary of the model describes the level of model i.e. fuel cell or fuel cell stack or system. Zero to three dimensional models comes from spatial dimensions. One-dimensional models are more suitable for the system level optimization. The models can come from a single discipline or multidiscipline. Consequently the model has its own level of complexity and details. For instance fuel cell models can be only electrochemical, thermodynamic or fluid dynamical or it can have all characteristics.

It is noteworthy that up to first half decade of this century there was available no transient system level model of fuel cell system except a stack level transient model (Amphlett *et al.*, 1996). Many researchers have adapted theoretical approach for modeling the fuel cell (Springer *et al.* 1991), (Fuller *et al.* 1993), (Yi *et al.*, 1998), (Dannenberg *et al.*, 1999) and (Boettner *et al.*, 2002) and some have adapted semi-empirical approach for instance (Kim *et al.* 1995), (Mann *et al.*, 2000). These models were steady state and fuel cell level only. Boettner and colleagues presented steady state system level model which included system components performance and control strategies. Amphlett and coworkers presented the transient fuel cell stack level in which heat management was discussed in detail.

Amphlett and others have obtained empirical models for the activation overvoltage and the internal resistance of the fuel cell. Activation over voltage was modeled as a function of temperature, current and oxygen concentration. The internal resistance was function of temperature and current. The hydrogen concentration was ignored in the modeling of activation overvoltage. The overall model of cell performance ionic and other losses were ignored. In their study single fuel cell was employed but latter on they have used fuel cell stack and results show that the parameters are different as empirical models have characteristics of specific system validity (Amphlett *et al*., 1995).

Baschuk and Li have presented one-dimensional, steady state, isothermal model assuming fully hydrated membrane. This model covers fundamental physical and electrochemical processes occurring in the membrane, catalyst layer and flow channels. Their modeling study focused on the water flooding in the cell. They investigated the effects of temperature and pressure of the cell on the flooding in the case of air and pure oxygen as reactant gases. They observed that air feed to the cathode is more effective than oxygen feed in decreasing the flooding with higher pressure and temperature but it is noteworthy that pressure and temperature effect the flooding at low and high current densities respectively (Baschuk & Li, 2000).

Rowi and Li have developed a PEM fuel cell mathematical model applying conservation laws for species and energy along with the Stefan-Maxwell, Butler-Volmer, Nernst-Plank equations and Fourier’s law. The fuel cell divided into five regions of electrodes, catalyst layers and membrane for modeling purpose. They investigated cell performance and thermal response under different temperature and water distributions in the cell. They concluded that the temperature profile is influenced by moisture in the electrodes at lower cell operating temperature or for unsaturated reactant streams. The cell performance is decreased due to reduced membrane hydration which is difficult to maintain at anode side in the presence of low water vapor diffusion coefficient despite of humidified reactant gas (Rowi and Li, 2001).

Baschuk and Li have developed a mathematical model of fuel cell with a sufficient detail covering main processes e.g. electrochemical reactions, proton migration and mass transport of reactant gases and liquid water. The all processes were explained in detail with clarity which develops good understanding of the different phenomena within cell. The multiphase model covers all regions of the cell and therefore becomes a complex model requiring CFD techniques for solution. This model does not look an ideal model for control purposes due to its complexity level (Baschuk and Li, 2004).

Amirinejad and colleagues have investigated the effects of pressure, temperature and humidity of reactant gases on performance of a single PEM fuel cell. They found that higher pressure and elevated temperature and humidified reactant gases can improve the cell performance (Amirinejad *et al.*, 2006).

Bao and colleagues used static model for pressure regulator and injection pump and further they neglected the accumulator dynamics by reducing the model i.e. they removed models of two components the regulator and the accumulator (Bao *et al.*, 2006).

Bao and coworkers focused on the topology and operating conditions of the air supply system. In the fuel cell modeling they have calculated the molar fraction of each species at the outlet of flow channel instead of the inlet molar fraction which leads to notable discrepancy as compared. This comparison is only among empirical and analytical models but it is misleading to conclude that outlet molar fraction is better that inlet molar fraction. They have claimed that up to 3% fuel cell stack efficiency can be improved but it is noted that parasitic loads are increasing and overall efficiency will be decreasing (Bao *et al.* 2006)

Bao and coworkers presented a mathematical model and simulated in Simulink/ Matlab environment so its block diagrams have been shown in detail. This model can be treated as dynamics / transient due to compressor dynamics, anode and cathode manifold filling dynamics. Static models were used for humidification of reactant gases and recirculation of hydrogen processes. In the membrane modeling water transport in MEA modeled by using Stefan-Maxwell equation considering electro-osmotic drag, back diffusion and convection as well. The authors mention the cathode flooding but they have given no detail. The simulation results of the model show that the authors failed to establish strong link among controls inputs and performance variables (Bao *et al.* 2006)

Grasser and Rufer introduced a model based approach to determine and optimize overall fuel cell system efficiency. System efficiency defined as ratio of net power of fuel cell system and power of fuel using higher heating value of hydrogen. System efficiency was optimized by choosing appropriate set points with equality constraint of net power function. Simulation results show agreement with general rule that overall efficiency becomes lower at higher current densities (Grasser and Rufer, 2006).

Bocaletti and colleagues presented a model to simulate the behavior of 75 KW fuel cell systems. They neglected thermodynamics of the system by considering the stack temperature as a parameter. The simulation results show that the model captured the reactant gases partial pressure dynamics. The transient behavior of the model was not validated nor compared but the results look logical and understandable. Moreover two different low and high temperature fuel cell models were compared through simulations and analyzed in detail (Bocaletti *et al.*, 2006).

Arsie and coworkers have described the dynamical behavior of hybrid vehicle. The vehicle contains fuel cell system, electric machine and batteries. The fuel cell system consists of fuel cell stack, compressor, humidification system and heat exchangers. The electric machine comprises of electric motor, converter and inverter. In the fuel cell modeling a constant voltage drop has been introduced from elsewhere (Rodataz *et al.*, 2003). This voltage drop caters for minor losses e.g. contact resistance, internal current, and leaks. They have modeled it as a function of operating pressure in the cathode. The parameters used in the models of activation, and concentration overvoltages have been correlated to operating pressure through empirical relationships (Arsie *et al.* 2007).

Grasser and Rufer have presented a model combination of steady state fuel cell stack submodel and dynamical submodel of auxiliary systems. In the polarization modeling four voltage losses i.e. activation, concentration, Ohmic and ionic were considered and detail description was given. Reactant gases transport phenomena has been modeled. Pressure driven and concentration difference driven transport were considered. Average oxygen fraction in the cathode gas channel and its concentration at the reaction site were calculated. Water transport influence the species concentration was calculated. Water transport phenomena in the membrane explained in detail. It relates to three different phenomena i.e. electro osmotic drag, diffusion and convection. This model takes into account Bernardi, Springer and Rowe models. The dynamic behavior of auxiliary components was considered. Air and hydrogen supply subsystem models and thermal management submodels have been presented with a state space models. The model was validated with Buchi and Rage data. Simulation results show that the error reaches to twenty percent at lower flow rates of reactant gases. Recirculation of hydrogen was mentioned only in their work but it was neglected for modeling (Grasser and Rufer, 2007).

Thanapalan and colleagues have presented a mathematical model and then validated on fuel cell station containing single fuel cell MEA. The model includes cathode and anode flows, the membrane hydration and voltage output. For validation purposes, the parameters of the voltage output expression were optimized by using direct search optimization methods. The model responses were compared with experimental data. The comparison showed a general agreement among them (Thanapalan *et al.*, 2008).

Caux and his colleagues have worked on air supply module of PEM fuel cell system. Their research was focused to electric train application having 400 KW power with 375V nominal voltage. Their major work was traction of Tramway power profile. For this purpose steady voltage output, they used an energy storage system with two DC /DC converters. First chopper boost the voltage whereas second chopper perform buck / boost bi-directional actions. For this scheme battery is essential which results in hybridization approach. They have totally neglected the influence of flow rate of reactant gases to regulate the output power despite they used constant pressures of reactant gases (Caux *et al.*, 2005 & 2005a). The model needs to be validated on a real system although it looks similar to the model already in the literature (Amphlett *et al.*, 1996).

3.2. Modeling & Control of PEM Fuel Cell System

Bao and colleagues introduced model-based controller for pressure tracking. At first stage they used static feed forward linear controller and then they switched over to adaptive nonlinear controller design. The former controller design assured good performance with limits due to inaccuracy of model and its linearization. Therefore latter design improved the control robustness and contained fuzzy neural network techniques. In their study humidification was totally neglected whereas recirculation at anode was adapted due to humidification advantages (Bao *et al.*, 2006).

Zenith and Skogestad have simulated a control system based on simplified model of high temperature PEM fuel cell with a DC / DC converter. The simulation could not be run over longer time spans with poor computational performance due to standard driving cycles. They also developed a mathematical tool to find conditions which guarantee the perfect control of fuel cells (Zenith *et al.*, 2007).

Ahn and Choe have described a mathematical model comprising of fuel cell stack, air supply and thermal submodels from Springer (1991), Ceraolo (2003), Gurski (2002) and Kroger (1984). Their study focused on the coolant system containing a bypass valve, a radiator with a fan, a reservoir and a pump. They have used classical controllers to control the stack temperature. During investigation they found that stack temperature has inverse relationship with oxygen excess ratio. They have worked a step forward to those works in which stack temperature assumed to be constant. Their control strategy assured reduction of paratactic load as well (Ahn *et al.*, 2008).

Wang and colleagues have devised a robust controller to keep the cell voltage output steady by regulating the input reactant gas flow rates using identified two input single output PEM fuel cell model. They have applied multivariable linear quadratic Gaussian control strategy. They claimed that the controller was effective in maintenance of steady output and reduced the fuel consumption as well (Wang *et al.*, 2008).

Puig and coworkers have proposed a model predictive control structure which uses not only compressor voltage as control variable but also cathode outlet valve area was utilized as control variable too. In this case the control performance was found better than when the controller with only first control variable was in action. The proposed controller introduced fault tolerance against compressor faults (Puig *et al.*, 2008).

3.3. Model Based Observers

Model-based observers, Salim *et al.*, (2009), Kandepu *et al.*, (2007), Kim *et al.*, (2007), Butt and Bhati, (2008), Qaiser *et al.*, (2008), Iqbal *et al.*, (2009a), Iqbal *et al.*, (2009b), Kazmi *et al.*, (2010), and Arcak *et al.*, (2004), are being used at large scale for the estimation of model parameters in industrial processes. These observers are also being used for control, diagnostics and communication (Forrai *et al*., 2005, Pukrushpan *et al*., 2002), (Gorgun *et al*., 2005, Pukrushpan *et al*., 2003), (Mays *et al*., 2001, Boutayeb *et al*., 2002) respectively. Different model-based techniques have been employed for the estimation of state and parameter e.g. Kalman (Salim *et al.*, 2009), Luenberger (Kandepu *et al.*, 2007), adaptive, and sliding modes (Kim *et al.*, 2007). Kalman observers need linearized models whereas Luenberger and adaptive observers require models of high accuracy and are sensitive to uncertainties and modeling errors. Sliding mode technique do not need linear model and is robust to modeling errors and uncertainties as well. Sliding mode observers (SMOs) are also simple in structure therefore the technique can be implemented easily that is why this technique is highly valued among the research community. It has been applied in variety of industrial applications in recent years but so far no SMO has been used for water content estimation. Kim and his coworkers designed nonlinear observer for the estimation of PEM fuel cell system wherein different pressures were estimated via SMO Kim *et al*., (2007). Butt and Bhatti employed the same technique for the parameter estimation of an automotive spark ignition engine Butt and Bhati, (2008). The parameters were discharge coefficient, indicated torque and load torque. Qaiser *et al*. developed the observer using same technique for the estimation of precursor concentration of a research reactor Qaiser *et al.*, (2008). Iqbal and his colleagues observed the parameter utilizing the sliding mode technique and then they employed higher order sliding modes for the fault diagnosis of uncertain nonlinear system Iqbal *et al.*, (2009a), Iqbal *et al.,* (2009b).

Arcak and colleagues have designed an adaptive observer for estimation of hydrogen partial pressure using measurements of voltage, current and total pressure. They found the speed of response and accuracy of the observer comparable with hydrogen sensors. The simulation results of their designed observer showed a good agreement with a commercial simulation model but at its low and higher power the results are not with agreement and showed a constant steady state error. They observed that the model of fuel flow through orifices is not correct and updation of coefficients of discharge resulted in good agreement (Arcak *et al.*, 2004).

Kim and coworkers have designed sliding mode observer for estimation of pressures in anode and cathode of PEM fuel cell system (Kim *et al.*, 2007). Its stability was proved by Lyapunov's stability analysis method. Their study was based upon their previous work published in a Japanese journal (Kim *et al.*, 2006).

It is obvious that there are different model based observers but in this work, sliding mode observer will be focused for parameter estimation and then for fault diagnostics of PEM fuel cell system due to its robustness and fast convergence.

3.4. Sliding Mode Observer

A sliding mode observer (SMO) is an observer which exploits sliding mode control theory for devise of an arrangement to minimize its error. The Sliding mode technique does not need linear model for observer design because of its inherent nonlinear characteristics and it holds for nonlinear systems. The technique is robust to modeling errors and uncertainties as well. The SMO is also simple in structure therefore it can easily be implemented. It is designed through two steps: in first step, a sliding surface is designed whose zero value confirms accomplishment of the task of observer. In the second step, a discontinuous nonlinear term is injected which ensures the sliding modes (Utkin, 1992). That is why this technique is highly valued among research community. It has been applied in variety of industrial applications in recent years by Kim *et al.*, (2007), Butt and Bhati, (2008), Qaiser *et al.*, (2008), Iqbal *et al.*, (2009a), Iqbal *et al.*, (2009b), and Kazmi *et al.*, (2010).

The standard SMO is utilized due to its characteristics of robustness and accuracy but the observed state exhibits the chattering effect. As the observer dynamics are concerned, this chattering effect does not matter. However if the observed state or parameter is to be used for controller implementation then the chattering effect may matter because such observer is noise sensitive and generate input vibrations. Therefore keeping an eye on future usage, the removal of chattering effect is addressed.

In the literature, there are a number of techniques which are used for mitigation of chattering phenomenon. The techniques include saturation approximation (Slotine and Li, 1991), averaging control effort (Utkin, 1992), sliding sector method (Furuta and Pan, 2000), terminal (Man *et al.*, 1994), dynamical (Sira-Ramirez, 1993), arbitrary (Levant, 2003 and Levant, 2005), and second order sliding modes (Emel'yanov, 1986, and Levant, 1993). However, the techniques experience tradeoff between removal of chattering and performance criteria i.e. robustness and accuracy. Some techniques need exact knowledge of system dynamics. Some techniques are not subject to Lyapunov stability analysis. Whereas the second order sliding mode (Emel'yanov, 1986, and Levant, 1993) mitigates the chattering effects preserving robustness and accuracy of standard sliding mode techniques. In addition, there is no need to have exact knowledge of system dynamics. A reasonable mathematical model is sufficient for its implementation. Its stability can be proved with the help of Lyapunov stability theory. Therefore it is a better choice to avoid the chattering preserving robustness and accuracy.

3.5. Fault Diagnosis in PEM Fuel Cell System

Fault diagnosis, preventing the system from entering faulty modes, can ensure the performance, reliability and durability of the system. The durability of the PEM fuel cell system is hot issue and different researchers are working in it. Major type of degradation of the PEM fuel cell system is caused by faulty operation modes of the system. The starvation of reactant gases, dehydration of membrane and flooding of electrodes. The health monitoring can be done via observation of mass flow rates of reactant gases and water dynamics of the system.

Riascos *et al.* (2008) have introduced a supervisor system that detects the PEM fuel cells faults on line. Their fault diagnostic scheme utilizes the measurement of voltage, current and temperature. In this scheme, the fault is detected and isolated by cause-effect relationship. They considered four faults namely fault in the air blower, fault in the refrigeration system, growth of fuel crossover & internal loss current and fault in hydrogen pressure. They employed Bayesian networks for fault diagnosis first time. The scheme requires a database of fault records. The voltage and current are fast variable but temperature variation is comparatively slow. Hence fault diagnosis in refrigeration system takes more time.

Tsushima and Hirai (2011) reviewed state of the art visualization techniques for diagnosis of water dynamics in PEM fuel cell systems. The swelling of membrane by water, accumulation of water inside the cells, and discharge of water were focused in their work. The techniques include neutron radiography, X-ray imaging, magnetic resonance imaging and optical visualization technique. The techniques provide in situ observations which give experimental support to understanding and then modeling the process. But they do not contribute to fault diagnosis in system on line.

Niroumand *et al.* (2011) introduced a diagnostic methodology for isolation of cathode flooding, cathode starvation and anode starvation using cell voltage oscillations. They concluded that fixed stoichiometry in the case of anode is reliable but not true in the case of cathode. Therefore they proposed a second order polynomial of current density for cathode stoichiometry. Their work did not cover the drying fault of cathode.

Chen and Zhou (2008) did experimental studies for diagnosis of PEM fuel cell stack dynamic behaviors. They correlated the stack voltage change with frequency of pressure drop across the cathode/anode. The technique needs guarantee that the finding of dominant frequency of pressure drop is accurate in the presence of noise.

Escobet et al. (2009) presented a model-based fault diagnosis methodology for PEM fuel cell systems using relative residual fault sensitivity analysis. The scheme did not require the knowledge of the fault magnitude. They discussed two fault scenarios only out of six fault scenarios in this work.

Hinaje et al. (2009) did experiments for online humidification diagnosis of a PEM fuel cell using a boost converter. The state of membrane humidification diagnosed using internal resistance of membrane that calculated from the voltage and current ripples. They highlighted additional use of converter as a diagnosis device for drying and flooding of fuel cell membrane.

3.6. Summary

The salient features of the above discussion can be concluded in the following points.

a. The model of cell performance was developed by many authors considering the different voltage losses in the fuel cell which includes activation losses, fuel crossover and internal currents, Ohmic losses, concentration losses and constant voltage drop. This model plays a key role in simulation of the fuel cell system. Some authors have modeled it with only one loss. Others have modeled with two losses (Barbir *et al.*, 2007) and with three losses (Boccaletti *et al.*, 2006) so on. But maximum losses have been catered for only four losses at a time. The model can be improved catering for five losses which would result in accurate cell performance.

b. In the air supply subsystem, compressors are used. The lookup table and neural network techniques were employed. There is a need of mathematical model of compressor for fuel cell system application that should be smooth function of its independent variables.

c. Different parameters which cannot be measured. The parameters include reactant concentration, reaction rates and partial pressures. Therefore there is a need of observer. So far hydrogen partial pressure has been observed via a nonlinear adaptive observer (Arcak *et al.*, 2004).

d. Humidification system is used as a static model. There is need of dynamic humidifying model.

e. The model can be made comprehensive catering for humidification, coolant and power conditioning sub models.

f. The controller for steady output voltage is employed controlling the entering the flow of reactant gases whereas others have controlled the output voltage through power conditioning. In the first case there are major draw backs where as power conditioning requires energy storage system.

g. During literature survey it is found that sliding mode techniques have not been employed for observation of parameters. So there is a provision for employment of the sliding mode designs. Recently, nonlinear controller designed using sliding mode strategy whose results are very good.
h. In the fuel cell system inherently there are many parametric and dynamic uncertainties. Therefore robustness of the system must be achieved by using robust controllers. In the literature H_∞ controller was employed using loop shaping design for generic uncertainty representation.

The literature survey may further conclude that the existing models for observation and control are not perfectly suitable. It means that there is a provision and scope for development of comprehensive mathematic model. Secondly there are many challenges for optimal operation of the system. They include voltage stabilization, oxygen and fuel starvation, water and thermal management. A number of states and parameters are not measureable or difficult to measure. Therefore there is a need of observers. The fault diagnostics is very critical and important issue for proper operation of the system. The sliding mode technique looks very suitable technique for the system due to robustness and fast convergence. The technique is easily implementable and has impressive characteristics of robustness, fast and finite time convergence.

Chapter 4

MASS FLOW RATE ESTIMATION

This chapter presents the synthesis of a model-based robust observer with an unknown input that observes a state (manifold pressure) of Fuel Cell System (FCS) in the presence of uncertainties. Using this observer the proportionality constant of the inlet manifold orifice is estimated. Then this estimated parameter is used to calculate the time varying air mass flow. As the mass flow rates of reactant gases play a pivotal role in the reliable and efficient operation of FCS. Their precise and exact value is necessary and important for the control and diagnostics of FCS. In the particular sense of inlet manifold of fuel cell system, appropriate air mass flow is very critical for the proper maintenance of chemical reactions taking place in the cathode and anode chambers. The sliding mode observer (SMO) with super twisting algorithm is utilized for the estimation of the mass flow rate of air despite the unknown input (load current). The estimates come out to be quite close to the nominal values. The simulation results show robustness to the uncertainties and fast convergence of estimates to nominal values of the parameter. The chattering phenomenon is attenuated significantly by employing higher order sliding mode. The standard SMO results are also presented for the sake of comparison. The proposed strategy is useful for sensor reduction, fault diagnostics and control.

4.1. Mass Flow Rate

Mass flow rate measurement is very important in the condition monitoring of fuel cells. In the conventional measurement method, the mass flow rates are derived from volumetric flow rates which are prone to ambient temperature and pressure effects. Therefore their measurement accuracy is not always satisfactory. However the direct measurement of mass flow rate is also under study and a few measuring devices have been developed such as coriolis and thermal flow meters on working principle of differential pressure instead of volumetric flow measurement. Unfortunately the direct methods have still some limitations and restrictions in practical applications. Therefore new direct methods are still under research (Hongjian *et. al.*, 2006).

In the calculation of mass flow rate, difference of fluid pressures at up/down streams is reduced by a factor. This factor can be named as proportionality parameter. If the pressures are known at the points then mass flow rate can be calculated in the conduit simply by multiplying pressure difference with proportionality parameter. In this work the proportionality parameter has been estimated via an observer, a dynamical system using input-output measurements. Model-based observers Salim *et al.*, (2009), Kandepu *et al.*, (2007), Kim *et al.*, (2007), Butt and Bhati, (2008), Qaiser *et al.*, (2008), Iqbal *et al.*, (2009a), Iqbal *et al.*, (2009b), Kazmi *et al.*, (2010), and Arcak *et al.*, (2004), are being used at large scale for estimation of model parameters.

4.2. Estimation of Mass Flow Rate via FOSMO

In this section, first order sliding mode observer has been designed. The observer estimates the parameter with fast convergence to its nominal value.

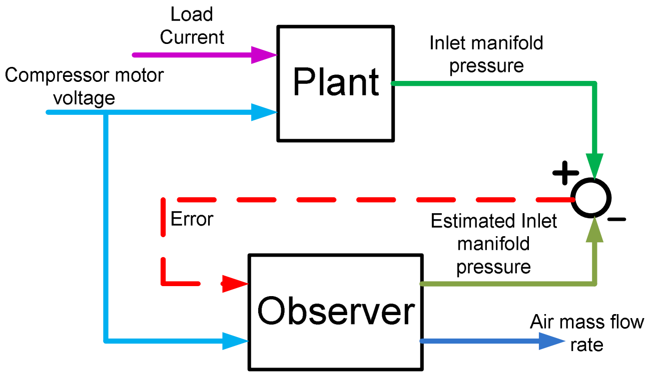


Figure 4.1: Plant and Observer Configuration

The observer is tested with simulations in configuration as shown in Figure 4.1. The load current input is unknown to the observer. The error is generated via comparing the measured and observed state i.e. inlet manifold pressure. The sliding mode observer estimates the parameter i.e. proportionality constant. Then this estimated parameter is used to calculate the mass flow rate of air that shows fast convergence to its nominal value with a negligible chattering phenomenon.

The fuel cell model consists of thirteen states including compressor speed and acceleration, mass flow rates of oxygen, nitrogen and vapors at inlet as well as at outlet manifolds, change in temperature, pressure of oxygen, nitrogen and vapors, hydrogen pressure, hydrogen mass flow rate, and water injected at cathode side (Carnes and Djilali, 2005). In the electrochemical model of stack the models are taken form (Ahluwalia and Wang, 2008). Since the work involves air dynamics of the FCS therefore only air breathing subsystem is considered of six states which are compressor speed, air pressures at inlet and outlet manifolds, mass flow rate of air, oxygen and nitrogen at inlet manifold (Kaytakoglu and Akyalcin, 2007). Mass flow rate of vapor has been taken having constant value. The air breathing schematic diagram is shown in Figure 4.2.

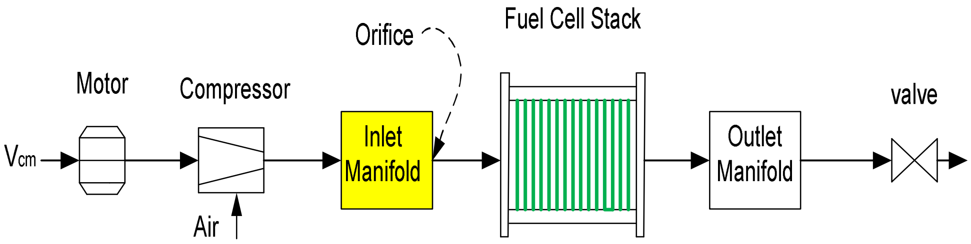


Figure 4.2: Air Breathing Subsystem Model

The air breathing submodel is formulated taking following assumptions.

- The gas obeys the ideal gas law.
- The spatial variations in inlet and outlet channels are ignored.
- The air dynamics in the channels and cathode are assumed as isothermal.
- The contribution of vapors in air is assumed constant.

The inlet manifold dynamics can be identified by filling and emptying model. The change in mass in the manifold is equal to the net mass flow rate between mass flow entering the inlet manifold and mass flow leaving the manifold as follows:

$$\dot{m}_{i\_m} = \dot{m}_{in} - \dot{m}_{out} \qquad \text{(Eq.}3.1\text{)}$$

The time derivative of inlet manifold pressure can be modeled as follows:

$$\dot{p}_{i\_m} = \frac{\gamma R_{air}}{V_{i\_m}}\left(\dot{m}_{cp}\, T_{cp} - \dot{m}_{i\_m}\, T_{i\_m}\right) \qquad \text{(Eq.3.2)}$$

Where mass flow rate leaving the inlet manifold can be calculated using linearized nozzle flow equation (Pukrushpan et. al., 2002):

$$\dot{m}_{i\_m} = K_{i\_m}\left(p_{\,i\_m} - p_{ca}\right) \qquad \text{(Eq.3.3)}$$

where K_{i_m} is the proportionality parameter. It scales down the pressure difference and gives mass flow rate out of the inlet manifold provided that the pressure difference is small. Putting equation 3.3 into equation 3.2, the following equation is obtained which contains three terms.

$$\dot{p}_{i\_m} = \frac{\gamma R_{air}}{V_{i\_m}}\, \dot{m}_{cp}\, T_{cp} - \frac{\gamma R_{air}}{V_{i\_m}} T_{i\_m}\, K_{i\_m}\, p_{i\_m} + \frac{\gamma R_{air}}{V_{i\_m}}\, T_{i\_m}\, K_{i\_m}\, p_{ca} \qquad \text{(Eq.3.4)}$$

The model shows that the rate of change in air pressure in the inlet manifold depends on the compressor flow into the inlet manifold, the flow out of the inlet manifold into the cathode and their temperatures.

In order to design the observer, the inlet manifold model can be simplified as follows:

$$\dot{p}_{i_m} = a - b\, K_{i\_m}\, p_{i\_m} + b\, K_{i\_m}\, p_{ca} \qquad \text{(Eq.3.5)}$$

For simplicity a and b are defined as follows:

$$a = \frac{\gamma R_{air}}{V_{i_m}}\, \dot{m}_{cp}\, T_{cp} \qquad \text{(Eq.3.6)}$$

$$b = \frac{\gamma R_{air}}{V_{i_m}}\, T_{i\_m} \qquad \text{(Eq.3.7)}$$

The equation 3.5 is perturbed by a small variation and takes the following form.

$$\dot{p}_{i_m} = a - b\left(K_{i\_m} + \Delta K_{i\_m}\right) p_{i\_m} + b\left(K_{i_m} + \ \Delta K_{i\_m}\right) p_{ca} \qquad \text{(Eq.3.8)}$$

The observer is designed on the perturbed model of inlet manifold model given by equation 3.8. The observer containing switching function with its β gain is as follows.

$$\dot{\hat{p}}_{i\_m} = a - b\,K_{i\_m}\,\widehat{p}_{i\_m} + b\,K_{i\_m}\,p_{ca} + \beta\Psi \qquad \text{(Eq.3.9)}$$

where switching function is defined as follows:

$$\Psi = \begin{cases} 1 & p_{i\_m} - \hat{p}_{i\_m} > 0 \\ -1 & p_{i\_m} - \hat{p}_{i\_m} < 0 \end{cases} \qquad \text{(Eq.3.10)}$$

The observer error is defined as the difference between inlet pressure and estimated inlet pressure as follows:

$$e = p_{i\_m} - \hat{p}_{i\_m} \qquad \text{(Eq.3.11)}$$

The observer has a task to steer its error to zero. The observer error dynamics equation is obtained by subtracting equation 3.9 from equation 3.8 as follows:

$$\dot{e} = -bK_{i\_m}e - b\Delta K_{i\_m}\left(p_{i\_m} - p_{ca}\right) - \beta\Psi \qquad \text{(Eq.3.12)}$$

If the observer steers its error to zero then the following relationship can be obtained from equation 3.12 for $e = 0$ and $\dot{e} = 0$.

$$\Delta K_{i\_m} = \frac{-\beta\Psi}{b\left(p_{i\_m} - p_{ca}\right)} \qquad \text{(Eq. 3.13)}$$

The stability analysis of observer is investigated by taking the proposed Lyapunov candidate function of quadratic form as follows:

$$V = \frac{1}{2}e^2 \qquad \text{(Eq. 3.14)}$$

According to Lyapunov conditions for globally asymptotically stability (Slotine and Li, 1991), it is to be ensured that the candidate function and its derivative are positive and negative definite respectively. Moreover the function is divergent at infinity. It is obvious that the function is positive definite due to its quadratic characteristics. Secondly its derivative must be negative definite which will ensure its asymptotic decay and convergence. Taking its derivates as follows:

$$\dot{V} = -bK_{i\_m}e^2 - eb\Delta K_{i\_m}\left(p_{i\_m} - p_{ca}\right) - e\beta\Psi \qquad \text{(Eq.3.15)}$$

The first term at right hand side of above equation is negative definite. Other two terms can be investigated for negative definiteness. The above equation can be rearranged as follows:

$$\dot{V} = -bK_{i\_m}e^2 + e\left\{b\Delta K_{i\_m}\left(p_{ca} - p_{i\_m}\right) - \beta\Psi\right\} \qquad \text{(Eq.3.16)}$$

The negative definiteness of derivative of candidate function demands the existence of following constraint. The constraint gives the lower bound of switching gain of the observer.

$$\beta < \left| b \Delta K_{i\_m} \left(p_{i\_m} - p_{ca} \right) \right|$$

The switching gain is governed by two variables i.e. inlet manifold temperature and pressure. The inlet manifold temperature will define the magnitude of the gain whereas the pressure will describe the region of the gain as well. The value of switching gain within the bounds will guarantee the stability.

4.3. FOSMO Simulation Results

The performance analysis of the observer design is conducted using simulations. The parameters for simulation are based on fuel cell prototype vehicle (Pukrushpan *et. al.*, 2004). The simulations are run with constant load i.e. 100 amperes current and compressor input voltage is varied from 100 to 250 volts in shape of stair as shown in Figure 4.3.

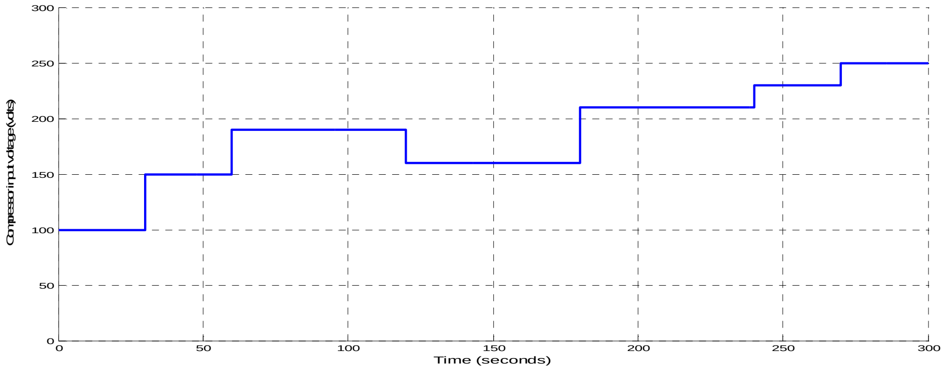


Figure 4.3: Compressor Input Voltage

The manifold pressure is observed. The results are very encouraging. The error remains in acceptable band that comes to less than one percent. The results are shown in Figure 4.4.

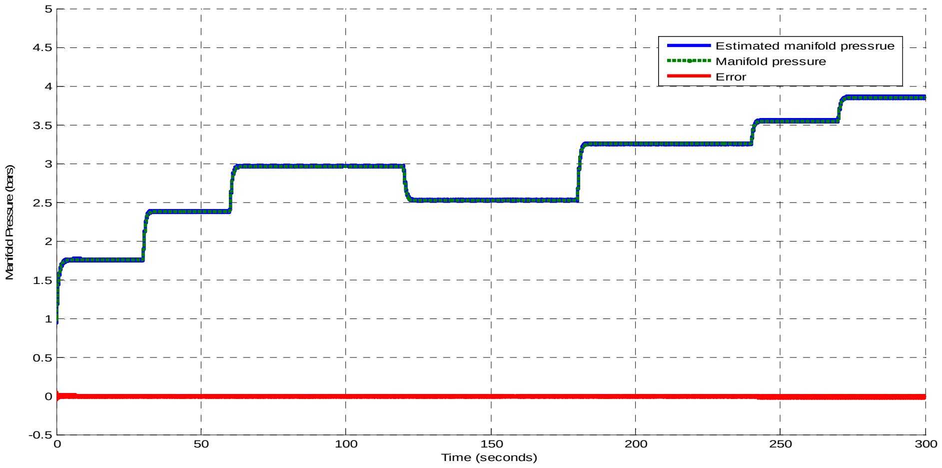


Figure 4.4: Manifold Pressure via FOSM Observer

The mass flow rate of air leaving the inlet manifold is estimated via sliding mode technique. The simulation result is shown in Figure 4.5. The figure shows that the estimator tracks the inlet manifold mass flow rate with an acceptable delay. The estimator shows an error in startup time but after approximately 25 seconds it tracks and estimates the mass flow rate very well.

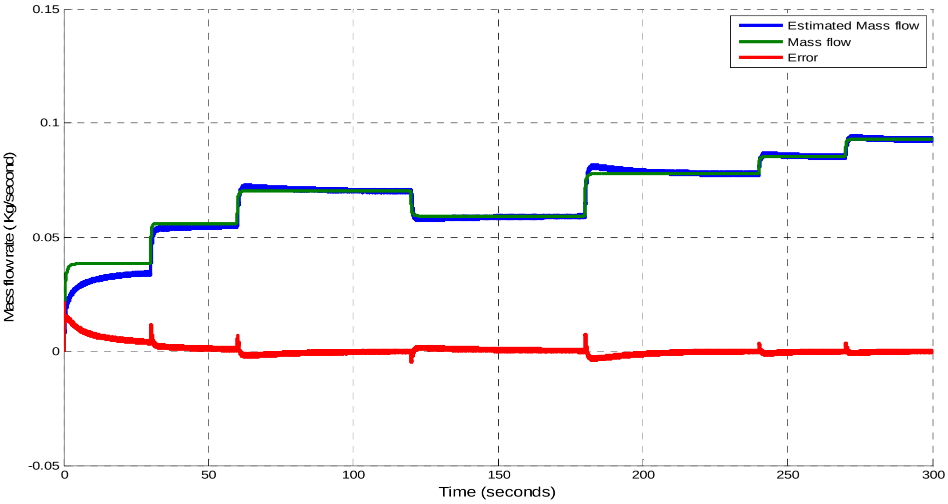


Figure 4.5: Mass Flow Rates via FOSM Observer

The results confirms that a nonlinear observer has been designed for estimation of oxidizer mass flow rate of fuel cell system (FCS) using estimated value of outlet orifice constant of inlet manifold. The observer design is based on first order sliding mode technique. The observer structure is simple hence it is easy for implementation. The robustness of observer has been seen in the results. The estimates are quite similar to nominal values but showing inherent chattering phenomenon. A higher order sliding mode observer is recommended for mitigation of chattering thus improvement of performance and accuracy. However the observer can replace the mass flow sensor which requires expensive and hard instrumentation for measurement of mass flow rate.

4.4. Estimation of Mass Flow Rate via HOSM Observer

In the previous work of authors, sliding mode observers were utilized due to their characteristics of robustness and accuracy. The estimated mass flow rate exhibited the chattering effect in Kazmi *et al.*, (2008). As the observer dynamics are concerned, this chattering effect does not matter. However if the observed mass flow rate is to be used for controller implementation then the chattering effect may matter because such observer is noise sensitive and generate input vibrations. Therefore keeping an eye on future usage, the removal of chattering effect is addressed in this work.

In the literature, there are a number of techniques which are used for mitigation of chattering phenomenon. The techniques include saturation approximation (Slotine and Li, 1991), averaging control effort (Utkin, 1992), sliding sector method (Furuta and Pan, 2000), terminal (Man *et al.*, 1994), dynamical (Sira-Ramirez, 1993), arbitrary (Levant, 2003 and Levant, 2005), and second order sliding modes (Emel’yanov, 1986, and Levant, 1993). However, the techniques experience tradeoff between removal of chattering and performance criteria i.e. robustness and accuracy. Some techniques need exact knowledge of system dynamics. Some techniques are not subject to Lyapunov stability analysis. Whereas the second order sliding mode (Emel’yanov, 1986, and Levant, 1993) mitigates the chattering effects preserving robustness and accuracy of standard sliding mode techniques. In addition, there is no need to have exact knowledge of system dynamics. A reasonable mathematical model is sufficient for its implementation. Its stability can be proved with the help of Lyapunov stability theory. Therefore it is a better choice to avoid the chattering preserving robustness and accuracy.

In the second order sliding mode, a hyper-plane is designed as a constraint function. In the case at hand, the error of actual manifold pressure and the observed manifold pressure is defined as the constraint function. The function and its derivative both are to be steered to zero. A theoretical problem formulation is discussed in detail next.

Consider an uncertain system having following structure taken from standard literature (Slotine and Li, 1991):

$$\dot{x} = f(t,x) + g(t,x)u + \varsigma(t), \qquad \text{(Eq.3.17)}$$

where $x \in X \subset \mathbb{R}^n$ is a state vector; $u \in U \subset \mathbb{R}$ is a bounded input, $\varsigma(t) \in W \subseteq \mathbb{R}^m$ is the unknown input (disturbance) and t is the independent time variable. The disturbance $\varsigma(t)$ is a Lebesgue-measureable function and is bounded i.e.

$$\|\varsigma(t)\| \le \varsigma^{+}. \qquad \text{(Eq.3.18)}$$

The sliding surface $s(t,x)$ is designed such that its zero value confirms the accomplishment of the design objective. The system dynamics can thus be written as (Levant, 1993)

$$\dot{s} = \phi(t,x) + \gamma(t,x)u. \qquad \text{(Eq.3.19)}$$

The dynamics in above equation are assumed to satisfy the following boundary conditions (Levant, 1993):

$$0 < \Gamma_{\mathrm{m}} \le \gamma(t,x) \le \Gamma_{\mathrm{M}}, \qquad \text{(Eq.3.20)}$$

$$|\phi(t,x)| \leq \Phi, \quad \text{(Eq.3.21)}$$

and

$$|s| \leq s_0, \quad \text{(Eq.3.22)}$$

---

where Γ_m, Γ_M, s_0 and Φ are some positive constants. Sliding mode observer is based on keeping exactly properly chosen constraints (sliding manifold) by means of high frequency control switching establishing a sliding motion. The main idea of higher order sliding modes is to act on higher order derivatives of sliding manifold variable as compared to the first order derivative in the standard sliding mode technique. There are a number of algorithms available in the literature e.g. real twisting and super twisting algorithms etc. In this work super twisting algorithm is selected because of its fast convergence and computational simplicity that arise from the absence of sliding manifold derivatives.

The algorithm is the most popular one among the second order sliding mode algorithms. The algorithm is robust to parametric uncertainties and disturbances subject to fulfillment of its conditions or bounds. The algorithm has been developed and analyzed for systems which can be written in the form equation 3.17 and satisfy the conditions given in equations 3.20 to 3.22. The super twisting algorithm that is given below converges in finite time (Levant, 1993).

$$u(t) = u_1(t) + u_2(t), \quad \text{(Eq.3.23)}$$

$$\dot{u}_1 = \begin{cases} -u & |u| > 1 \\ -W sign(s) & |u| \leq 1, \end{cases} \quad \text{(Eq.3.24)}$$

$$u_2 = \begin{cases} -\lambda |s_0|^{\rho} sign(s) & |s| > s_0 \\ -\lambda |s|^{\rho} sign(s) & |u| \leq s_0. \end{cases} \quad \text{(Eq.3.25)}$$

The injector comprises of two terms; first term is discontinuous time derivative and the second term is function of sliding surface. The corresponding sufficient conditions for finite time convergence are:

$$W > \frac{\Phi}{\Gamma_{\mathrm{m}}} > 0, \qquad (\mathrm{Eq.}\,3.26)$$

$$\lambda^2 \geq \frac{4\Phi\Gamma_{\mathrm{M}}(\mathrm{W}+\Phi)}{\Gamma_m^3(\mathrm{W}-\Phi)}, \qquad (\mathrm{Eq.}\,3.27)$$

and

$$0 < \rho \leq 0.5. \qquad (\mathrm{Eq.}\mathit{3.28})$$

When the ρ is unity, this algorithm converges to the origin exponentially.

The fuel cell model has matched and system uncertainties both. The matched uncertainty is the function of compressor motor speed and compressed air temperature. For the boundedness of the uncertainty, the compressor motor speed does not become zero at any instant during operation of the system. The load current of the system is system uncertainty that acts as a disturbance to the system.

In order to design the observer, the inlet manifold model can be simplified as follows:

$$\dot{p}_{i\_m} = a - b\,K_{i\_m}\,p_{i\_m} + b\,K_{i\_m}\,p_{ca}, \qquad (\mathrm{Eq.}\mathit{3.29})$$

where a and b are defined for simplicity as follows:

$$a = \frac{\gamma R_{air}}{V_{i_m}}\,\dot{m}_{cp}\,T_{cp}, \qquad (\mathrm{Eq.}\mathit{3.30})$$

$$b = \frac{\gamma R_{air}}{V_{i_m}}\,T_{i\_m}, \qquad (\mathrm{Eq.}\mathit{3.31})$$

The equation 3.29 is perturbed by a small variation and the equation takes the following form.

$$\dot{p}_{i\_m} = a - b\left(K_{i\_m} + \Delta K_{i\_m}\right) p_{i\_m} + b\left(K_{i\_m} + \Delta K_{i\_m}\right) p_{ca}\,. \qquad \text{(Eq.3.32)}$$

The observer is designed on the nominal model of inlet manifold given by equation 3.32. The super twisting observer is as follows.

$$\dot{\hat{p}}_{i\_m} = a - b\, K_{i\_m}\, \hat{p}_{\,i\_m} + b\, K_{i\_m}\, p_{ca} - \upsilon\,, \qquad \text{(Eq.3.33)}$$

where injector υ contains two terms i.e. discontinuous time derivative and continuous function of sliding surface. The modified switching function is defined as follows:

$$\upsilon(t) = \upsilon_1(t) + \upsilon_2(t) \qquad \text{(Eq.3.34)}$$

$$\dot{\upsilon}_1 = -W sign(s) \qquad \text{(Eq.3.35)}$$

$$\upsilon_2 = -\lambda\ \ |s|^{\rho}\ \ sign(s) \qquad \text{(Eq.3.36)}$$

The values of coefficients are $W = 0.5$, $\lambda = 10$, $\rho = 0.89$. The variable s denotes the sliding surface i.e. error between measured and observed inlet manifold pressures. The observer error can be expressed as follows:

$$s = p_{i\_m} - \hat{p}_{i\_m}\,. \qquad \text{(Eq.3.37)}$$

The observer has a task to steer its error to zero. The observer error dynamics equation is obtained by subtracting equation 3.33 from equation 3.32 as follows:

$$\dot{s} = -bK_{i\_m}s - b\Delta K_{i\_m}\left(p_{i\_m} - p_{ca}\right) + \upsilon\,. \qquad \text{(Eq.3.38)}$$

If the observer steers its error to zero then the following relationship can be obtained from equation 3.38 for s$= 0$ and $\dot{s} = 0$.

$$\Delta k_{i\_m} = \frac{\upsilon}{b\left(p_{i\_m} - p_{ca}\right)}\,. \qquad \text{(Eq. 3.39)}$$

The stability and convergence analysis of observer are investigated in detail in (Levant, 1993), (Levant, 2007) and (Fridman and Levant, 2002).

4.5. HOSMO Simulation Results

The higher order sliding mode observer design is tested on simulations for tracking, robustness and chattering phenomena. The parameters for simulation are taken from Pukrushpan *et al.* (2004). The simulations are run with fixed step size of 0.01 seconds using ode1 solver. To show the tracking ability of observer, load current is kept constant and compressor motor voltage is varied from 100 to 250 volts as shown in Figure 4.6. This input is known to the observer but second input that is load current is not known to the observer. Therefore, the observer can be considered as partial known input observer (PKIO).

Secondly, to show the robustness of the observer, the load current which acts as a disturbance is varied as shown in Figure 4.6. The matched uncertainty comes from variable motor speed automatically and other time varying parameter is temperature of compressed air. In this work, the objective is to mitigate the chattering phenomenon by using higher order sliding mode (HOSM) technique therefore the results are presented in the comparable format. It is noticeable that FOSM observer results are made readable via a low pass filter.

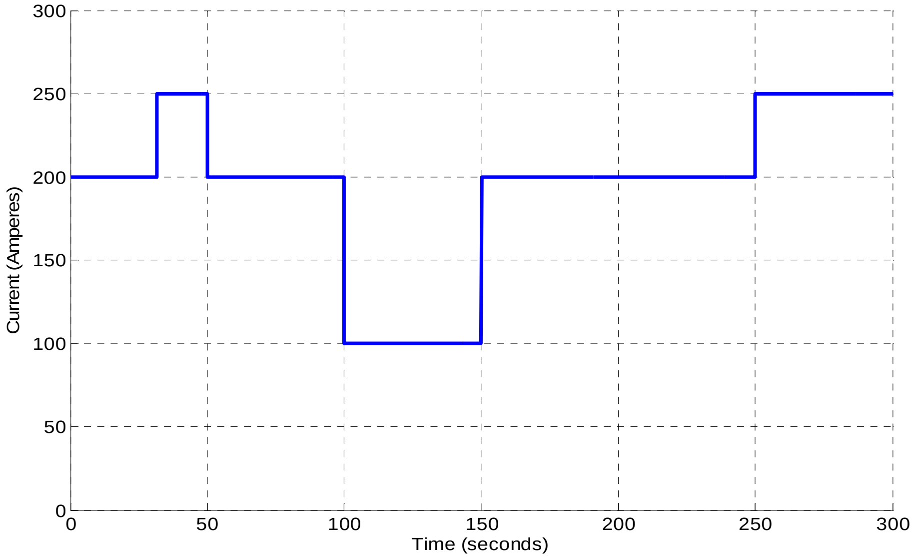


Figure 4.6 Profile of Load Current

4.5.1. Tracking Analysis

The inlet manifold pressure is observed and results are shown in Figure 4.7(a) and Figure 4.7(b) through HOSMO and FOSMO respectively. The results are very encouraging due to narrow band of error.

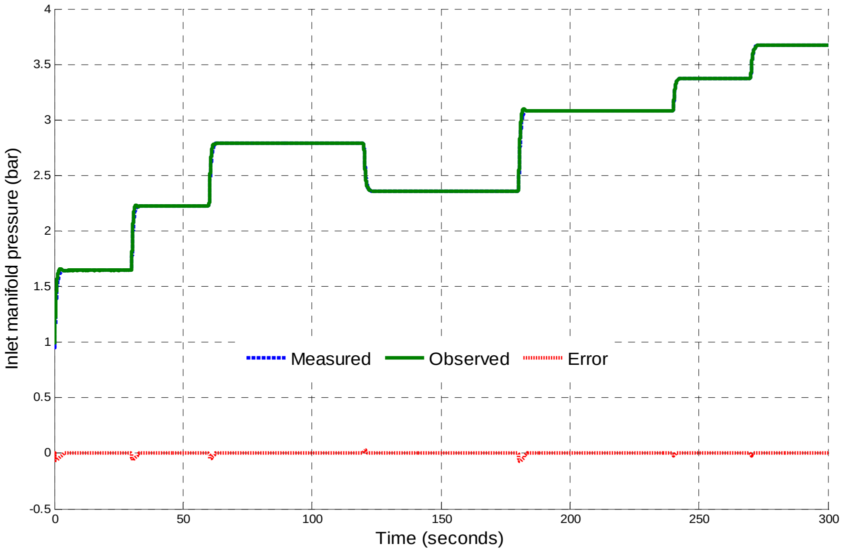


Figure 4.7(a): Manifold pressure via HOSM Observer

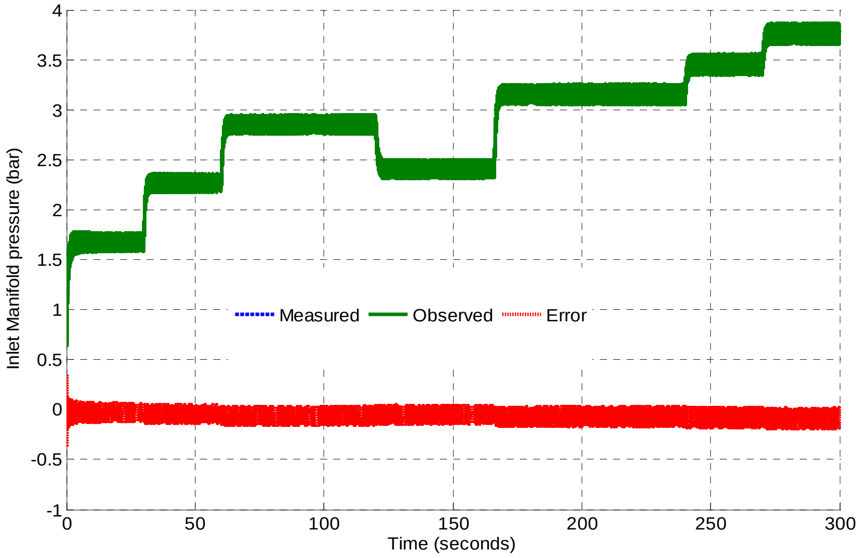


Figure 4.7(b): Manifold pressure via FOSM Observer

The mass flow rate of air leaving the inlet manifold is observed through HOSMO and FOSMO and results are shown in Figure 4.8(a) and Figure 4.8(b) respectively. The Figures depict that the estimator tracks the inlet manifold mass flow rate with an acceptable delay. The estimator shows an error in startup time but after approximately 25 seconds it tracks and estimates the mass flow rate very well. The results are similar but without chattering in Figure 4.8(a).

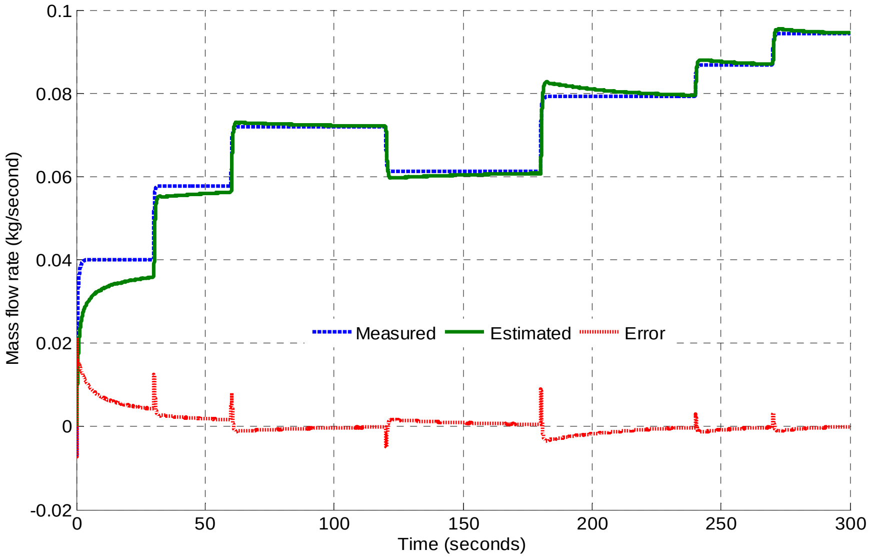


Figure 4.8(a): Mass flow rates via HOSM Observer

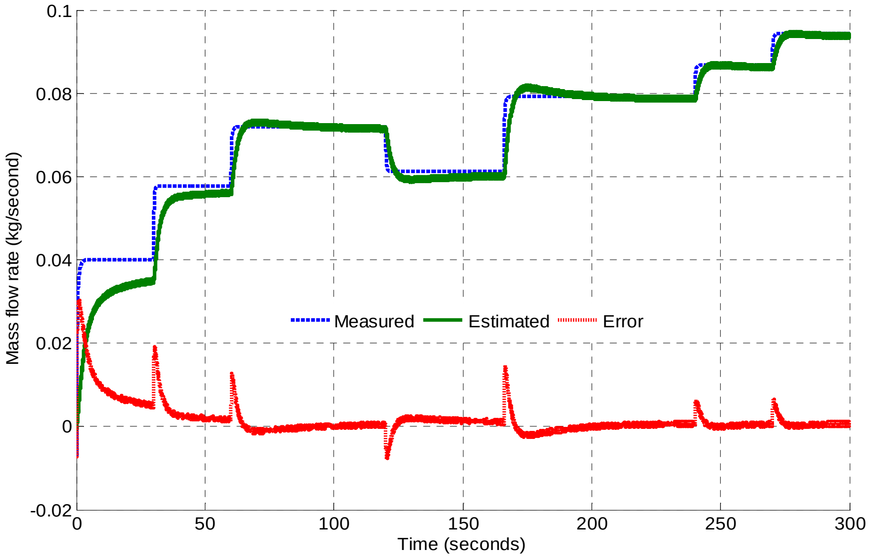


Figure 4.8(b): Mass flow rates via FOSM Observer

4.5.2. Robustness Analysis

The load current is considered as a disturbance in fuel cell system. The load dictates the consumption of oxygen at cathode. The changes in the load generate the problem of a control challenge of oxygen starvation. The results show that the observer is robust and insensitive to load disturbances generally. The results of observer under disturbance are shown in Figure 4.9 and Figure 4.10.

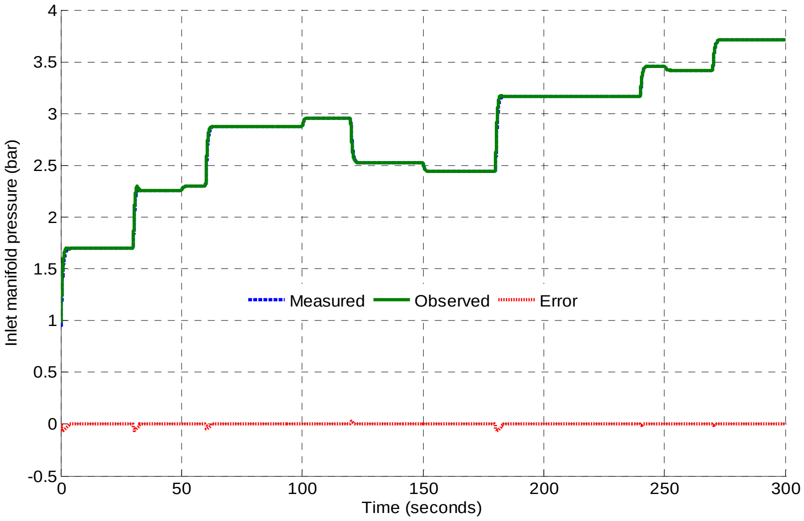


Figure 4.9(a): Manifold pressure under disturbance via HOSM Observer

The simulation results via second order sliding mode are shown in Figure 4.9(a). The robustness can be seen at the given time instants. The FOSM observer results are also shown in Figure 9(b) for reference only.

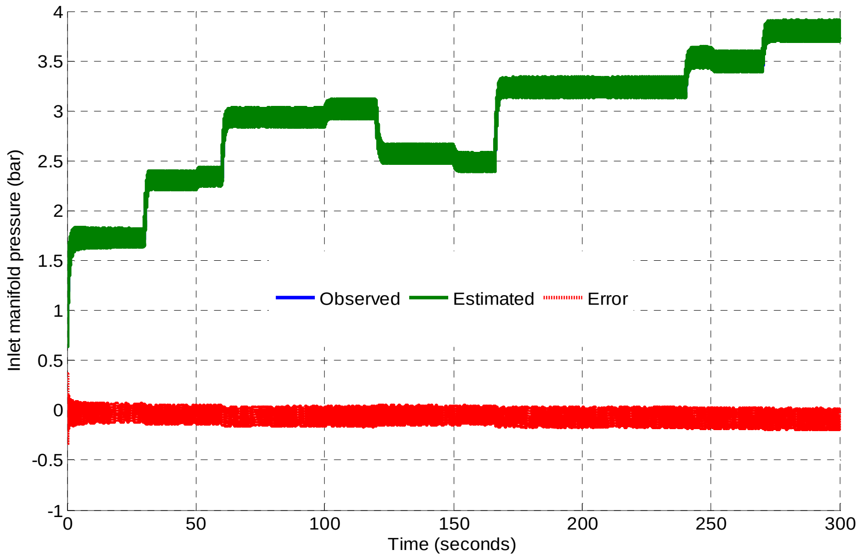


Figure 4.9(b): Manifold pressure under disturbance via FOSM Observer

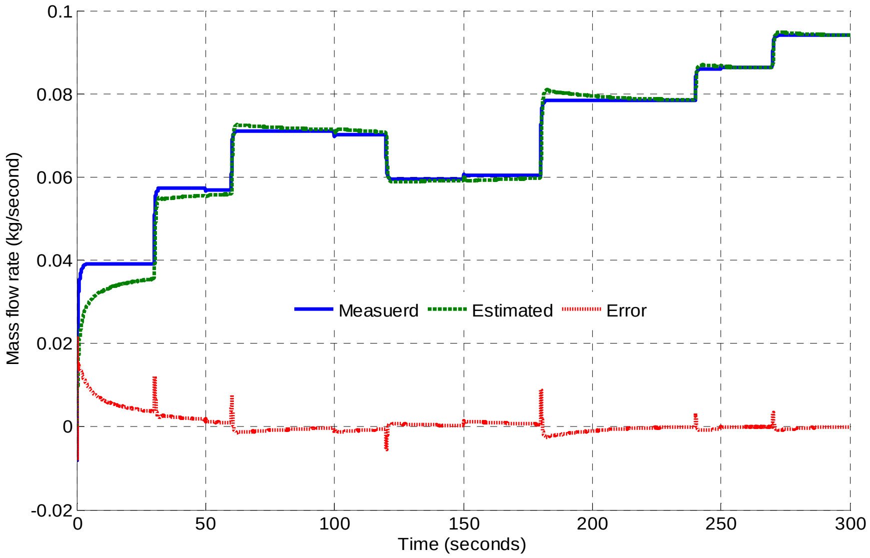


Figure 4.10(a): Mass flow rates under disturbance via HOSM Observer

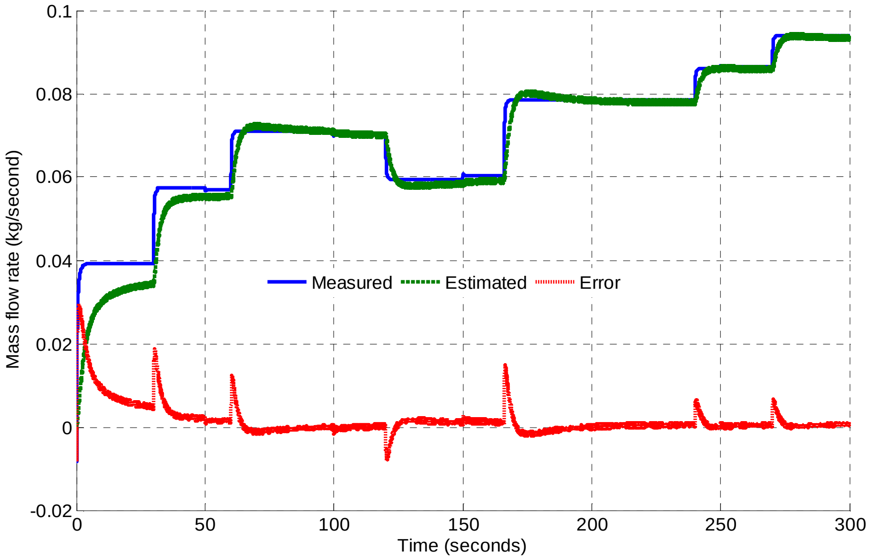


Figure 4.10(b): Mass flow rates under disturbance via FOSM Observer

4.5.3. Chattering Analysis

The HOSM observer demonstrates the robustness and performance similar to FOSM observer but without the chattering fatigue. The correction variable shows smoothness in its nature as shown in Figure 4.11(a) contrary to FOSMO injector shown in Figure 4.11(b) therein switching is very obvious in wide band.

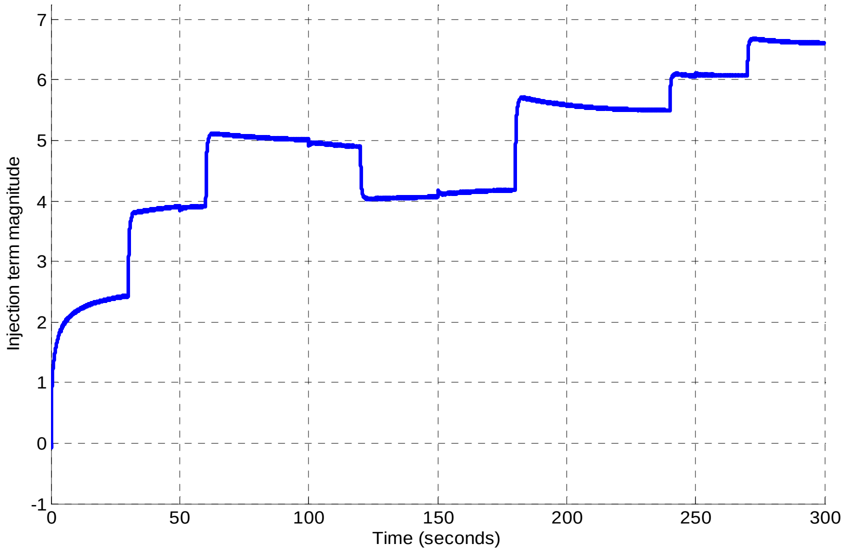


Figure 4.11(a): Injector without chattering via HOSM observer

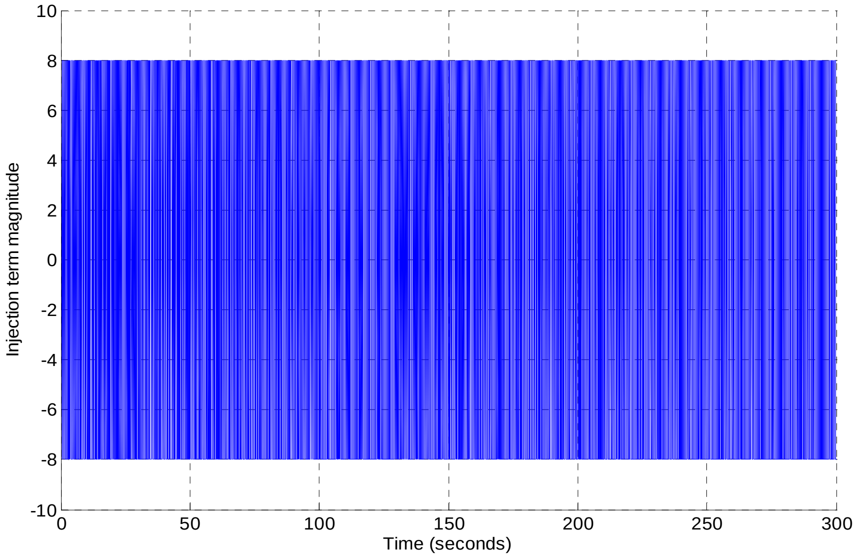


Figure 4.11(b): Injector with chattering via FOSM Observer

The error plots are also shown in Figure 4.12 that depicts the real attenuation of chattering effect.

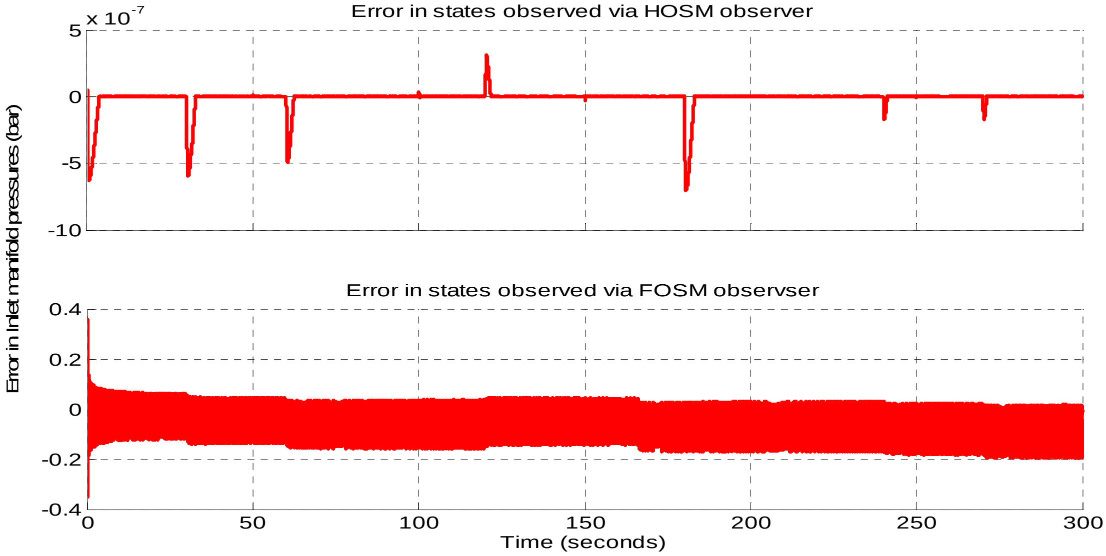


Figure 4.12: Error Plots of Inlet Manifold Pressures

The high frequency oscillations are harmful to many classes of system especially mechanical system. The observer has attenuated the chattering phenomenon preserving the performance characteristics of observer.

4.6 Summary

The salient features of the above discussion can be concluded in the following lines. The observers were designed for the estimation of oxidizer mass flow rate of fuel cell system (FCS) using estimated value of outlet orifice constant of inlet manifold. The observer designs were based on first and second order sliding mode techniques. The observer structure is simple hence it is easy for implementation. The robustness of observer has been seen in the results. The estimates are quite similar to nominal values without chattering phenomenon. The observer can replace the mass flow sensor eliminating expensive and hard instrumentation for measurement of mass flow rate. The second order sliding mode observer appears in a smooth shape and can be used for controller design without chattering phenomenon. The observer accomplished its task even in the absence of an input.

Chapter 5

WATER CONTENT ESTIMATION

Water content is a critical parameter that affects proton conductivity of perfluorosulfonate membrane in PEM fuel cells. The decreasing water content degrades the proton conductivity. On the other hand, abundant water content blocks the flow of reactant gases to catalyst. Therefore water management is one of the major issues in the proper operation of the system. This issue is dealt with different approaches that include designing membrane electrode assembly, hardware & system design and controlling of stack operating conditions. The former approach rests with manufacture's part and may include cell orientation at 45 degrees towards air outlet port and cell shaking during fuel cell operation. Later methodology concerns with fuel cell system operation and may include maintaining of operating temperature, pressure, stoichiometry and the humidification levels of reactant gases. Water management consists of three stages i.e. water treatment, humidification of reactant gases and water removal process. But all these remedies are feasible at that time when water content level is known in the stack and can be monitored efficiently. This chapter describes water content estimation employing higher order sliding mode observer. The design of observer is based on a dynamic voltage model of PEM fuel cell stack. The development of the model is described in detail. The results are verified by offline calculation of water content parameter. The parameter estimation supports the fault diagnosis of flooding and drying scenarios of the PEM fuel cell system.

5.1. Water Transport Dynamics

During operation of the system, the water is produced at the cathode. The presence of water contents in the stack is sensitive to cold environment, reactant gases transportation, proton conductivity and length of membrane life. In the cold environment, the water content can change its phase in the stack due to subfreezing temperature. In this scenario, the water content can increase start-up time of the system. Insufficient and excessive amount of water content in the stack affects negatively the performance of fuel cell system. The inadequate amount of water can cause the membrane dryness and then would create cracks in the membrane. The dry membrane has higher internal resistance which increases the voltage losses. The cracks in the membrane degrade the performance and shorten the stack life. On the other side, the excessive water content causes flooding in the stack and fills the pores of the porous gas diffusion layer and prevents the distribution of the reactants to the catalyst. The situation becomes severe at high current densities. This state occurs not only at cathode side but the anode also gets affected. The produced water at the cathode diffuses into the anode side due to the gradient of water concentration. The anode having close end at outlet side is severe victim of the process because water accumulates there and hinders the adequate distribution of fuel gas distribution.

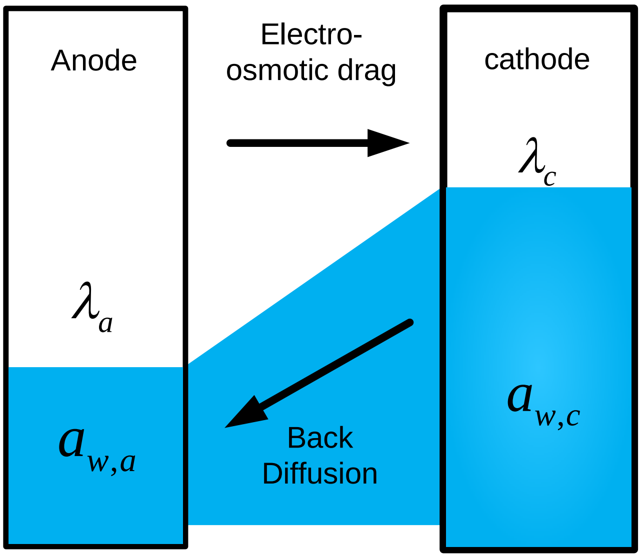


Figure 5.1: Schematic Diagram of water dynamics

Automotive system experiences numerous power transients. The water dynamics during theses transients affects performance and durability of the system. Actually in the stack, there are two processes of electro-osmotic drag and back diffusion of water across the membrane as shown in Figure 5.1. The water content parameter λ is the average of both parameters λ_c and λ_a at the cathode and anode respectively.

5.2. Water Content Parameter

Water content measurement is very important in the condition monitoring of fuel cells. In the conventional measurement method, the humidity sensors are used which are prohibitive for in-situ measurement due to their size and cost. Their accuracy is also not always satisfactory for high relative humidity levels. However the gas chromatography technique is relatively accurate but it needs extractive sampling which makes it slow and intrusive. Other techniques such as neutron radiography and real-time gas analyzer have their own issues. The optical devices which access the water fronts and distribution in transparent cell plates are used for direct visualization. The optical devices may include digital camcorders, high-speed cameras, infrared cameras and Charge-Coupled Device (CCD) cameras. Nuclear Magnetic Resonance (NMR) imaging or Magnetic Resonance Imaging (MRI) is used for measuring water distribution of an operating fuel cell in situ. Beam interrogation approaches include neutron imaging, electron microscopy, X-rays techniques. Fluorescence microscopy provides the micro scale transport of liquid water (Mengbo and Zidong, 2009). All these techniques can be employed for offline analysis and diagnostics. In the controlling of operating parameters, online estimation is required for control and diagnostics purposes. There are numerous works reported in the literature therein water management has been given vital importance for good performance of the system developing mathematical models, analyzing process and devising detection techniques of water management.

Several research efforts focused the development of theoretical models to capture the water dynamics in the stack for water management over the last decade. Siegel and Stefanopoulou (2009) developed a mathematical model to predict the slowly evolving water front locations in both anode and cathode side gas diffusion layers during flooding and drying as well as the dynamic changes in membrane water content. Ahmed and Chmielewski (2009) developed a model and studied membrane hydration and its profile. They identified manipulating parameters as anode bubbler temperature, cathode bubbler temperature and solid set point temperature. Through manipulation of the parameters, average water content can be maintained. They also showed the relationship between flow of water contents from cathode to anode and vice versa with change in power of the system. At low power levels only water flows from cathode to anode whereas at high power level water flows across the membrane in both ways. Paquin and Frechette (2008) analyzed the cathode flooding using mathematical model and experimentation. Their analysis was based on two resistances; one is due to temperature and other relates to mass flow of reactant gas. They studied the effect of both resistances on water balance. Ultimately, they succeeded to develop a performance parameter of ratio between two resistances. This application restricted only to air breathing systems and they neglected the diffusion process of water content from cathode side.

In order to validate and verify the model and to search the capable methods for water management, many studies carried out on physical system. Weng *et al*. (2006) studied cathode flooding and verified it via visualization of water flooding by using transparent fuel cells. The effect of cathode gas concentration was discussed. Liquid water can be easily removed at high cathode gas flow rate but at parallel it can degrade the membrane. It suggests that the monitoring of water content is necessary. Ahamd *et al*. (2009) investigated the behavior of water production by constructing a transparent cathode PEM fuel cell. They studied the effect of different operating conditions on the production of water content. They established that water production is directly proportional to current density & humidification whereas its stoichiometric ratio constant is inversely proportional to water. Mughal and Li (2006) studied work on water management focusing on water removal techniques experimentally. The techniques were cell orientation, shaking of cell and hydraulic permeation. The water removal stage came after the knowledge of water content level. They did not discuss about the monitoring or measurement of water flooding.

Various schemes were devised to detect and predict the water content level in the stack in recent years. Thawarnkuno and Panjapornpon (2008) proposed a technique to predict the water content using state estimation. They estimated the water content via extended Luenberger observer. This technique demonstrated results better comparably while open loop observer was used. Judith O’Rourke *et al.* (2009) suggested a detection scheme of anode flooding earlier than a fast voltage negative spike occurrence. This scheme is applicable at low current densities because anode flooding occurs at low current densities. This scheme requires voltage scan cards, median voltage calculation and a circuit to spike current load. McKay and Stenfanopoulou (2004) developed and then validated mathematical model for membrane humidity in the stack. They used open loop observer to estimate the humidity. Gorgun *et al.* (2005, 2006) proposed an algorithm for the estimation of water content in PEM fuel cell exploiting its effects on cell resistance voltage drop. The algorithm requires measurements of voltage, current, temperature and total pressure values in the cathode and anode. Using these measurements they calculated the membrane resistance and then an estimate of water content is obtained analytically. The scheme cannot be applied for zero or small value of current whereas anode flooding occurs at low current densities. Another problem with this scheme is that a number of estimators are required for observation of partial pressures of hydrogen and oxygen etc. They did not incorporate flooding conditions instead they monitored the pressure drop at cathode side to distinguish between flooding and drying conditions only.

5.3. Development of Dynamic Voltage Model

Fuel cell stack consists of many fuel cells connected in series to obtain a useful voltage because a single fuel cell can generate single volt approximately that is not sufficient voltage for any application. The stack voltage therefore can be calculated as

$$V_{stack} = n \times V_{fc}, \qquad \text{(Eq. 5.1)}$$

where V_{stack} is the voltage of stack, n is the number of fuel cells and V_{fc} is the voltage of a single fuel cell. The stack current depends upon the active area of fuel cell and passes through each fuel cell. Therefore the stack current can be calculated as

$$I_{stack} = i \times A_{fc}, \qquad \text{(Eq. 5.2)}$$

where I_{stack} is the stack current, i is the current density (Amperes per unit fuel cell active area) and A_{fc} is the area of fuel cell. The power of fuel cell can be calculated as

$$P = V_{stack}\ I_{stack}, \qquad \text{(Eq. 5.3)}$$

where P is the power of fuel cell system. The net power of fuel cell system can be found by deducting the parasitic loads from the total power. The open circuit voltage is an electromotive force. It represents the maximum theoretically achievable voltage depending upon the operating pressure and temperature of reactant gases. Almost all models calculate the theoretical voltage using Nernst equation, for instance Larminie and Dicks (2003), Balkin (2002), Brunetto *et al*. (2004), Correa *et al*. (2004), Cheng *et al*. (2006), Arsie *et al*. (2007). Keonyup *et al*. (2007), Amphlett (1995),Boccaletti (2006) and Busari *et al*. (2006). The Nernst model is given as

$$E_{Nernst} = \frac{\Delta G}{zF} + \frac{\Delta S}{zF}\left(T - T_{ref}\right) + \frac{RT}{zF}\left(ln\left(p_{H_2} + \frac{1}{2}p_{O_2}\right)\right), \qquad \text{(Eq. 5.4)}$$

where ΔG is the change in the free Gibbs energy (J/mol); z is the number of electrons exchanged per molecule of hydrogen; F is the constant of Faraday (96,487 C); ΔS is the change in entropy (J/mol), R is the universal constant of the gases (8,314 J/K mol); while p_{H_2} and p_{O_2} are the partial pressures of hydrogen and oxygen respectively (atm). Variable T denotes the cell operating temperature (k) and T_{ref} is the reference temperature. Using standard pressure and temperature (SPT) for ΔG, ΔS and T_{ref}, we get open circuit voltage as follows:

$$V_{OC} = 1.229 - 0.85 \times 10^{-3}(T - T_{ref}) + 4.31 \times 10^{-3}\left(ln\left(p_{H_2} + \frac{1}{2}p_{O_2}\right)\right). \qquad \text{(Eq. 5.5)}$$

The fuel cell voltage is always less than the theoretical voltage implying that there are voltage losses. Therefore the net fuel cell voltage is equal to open circuit voltage deducting the voltage losses in the fuel cell. This can be expressed mathematically as

---

$$V_{fc} = V_{OC} - V_{loss} \qquad \text{(Eq. 5.6)}$$

---

where V_{OC} is the open circuit voltage and V_{loss} is the voltage loss. A typical polarization curve is shown in Figure 5.2. The fuel cell voltage is less than the theoretical voltage. Mainly, three regions are shown in Figure 5.2 representing activation, Ohmic and concentration losses. These losses are discussed in detail in the following lines.

5.3.1. Activation Losses

The activation loss is a measure of voltage drop associated with the electrodes only and is estimated up to fifty percent of the total voltage loss. Therefore, it is major loss to the total voltage. The slowness of the electrochemical reactions on the electrode surfaces causes these losses while the reactions are being driven from equilibrium for electricity generation. These losses increase as the current drawn increases. Activation losses are mostly relevant at low current densities and are highly nonlinear but theses losses affect the voltage at intermediate and high current densities as well.

Activation losses are high at low temperature of the fuel cell and are not significant at high temperature. Oxidation of hydrogen at anode side is hundred times faster than reduction of oxygen at cathode. Therefore, the chemical reaction only at cathode limits the overall phenomena significantly. Due to this, the activation losses at anode side are neglected generally.

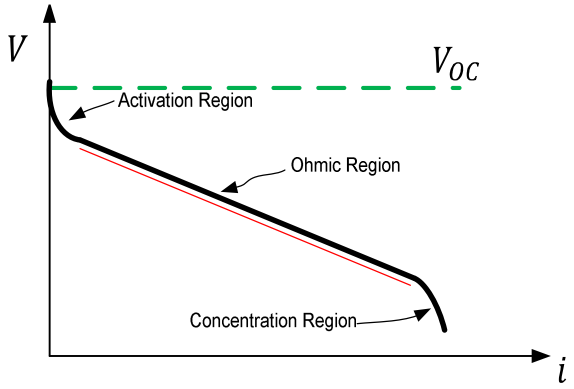


Figure 5.2 Typical Fuel cell polarization curve

As shown in Figure 5.2, the steep initial decrease represents the activation losses at low current densities. This segment is a vertical line starting from theoretical value of the cell voltage to some point on the vertical axis. At intermediate and high current densities, the curve of the activation losses is a diagonal line, collinear with the polarization curve which starts from end of first segment. Numerous mathematical models of activation losses are available in the open literature Siegel and Stefanopoulou, (2009), Ahmed and Chmielewski (2009), Paquin and Frechette (2008), Weng *et al.* (2006), Mughal and Li (2006), Thawornkuno and Panjapornpon (2008), O'Rourki and Arcak (2009), Mckay and Stefanopoulou (2004), Gorgun *et al.* (2005, 2006). The activation losses are usually modeled by using either Tafel equation or Butler-Volmer equation. Amphlett and his coworkers (1995, 2008) developed an empirical model which is a function of stack temperature, oxygen concentration and current density. This model captures the phenomena that activation losses decrease with the rise in the temperature and oxygen concentration. At low current density, activation losses are increasing. Arsie and his coworkers (2007) developed a model which is the function of temperature current density using Tafel equation. They modeled the exchange current density as a second order polynomial of the cathode pressure. In this model, the anodic contribution is neglected. They considered the reactant concentration using the cathode pressure. Boccaletti and her colleagues (2006) developed the model using the result that the activation losses are proportional to natural logarithmic value of current density. Bao and his colleagues (2006a, 2006b) used the model which depends upon temperature, current density and oxygen concentration. They employed Tafel equation using the electron transfer coefficient as a constant for whole phenomena. Buasri and her colleagues (2006) developed model for activation losses similar to Boccaletti *et al*. (2006) but argument of natural logarithm is ratio of load current and a constant value of current of 0.074 amperes. Correa *et al.* (2004) presented an empirical model same as Amphlett (2008). They developed an expression for calculation of oxygen concentration. This expression is a function of the oxygen partial pressure at cathode and the stack temperature. Mert and his colleagues (2007) developed a model for both cathode and anode contribution to the activation losses by finding respective electron transfer coefficients separately. The model was function of temperature, current density and exchange current density. They developed an empirical model for the current exchange density which is a function of temperature only. J.T. Pukrushpan *et al.* (2006) presented a model for calculation of the activation losses using Tafel equation as

$$V_{act} = V_0 + V_a\left(1 - e^{-C_1 i}\right), \qquad \text{(Eq. 5.7)}$$

where $C_1 = 10$,

$$V_0 = 0.279 - 8.5 \times 10^{-4}\left(T_{fc} - 298.15\right) + 4.3085 \times 10^{-5} T_{fc} \left[ln\left(\frac{p_{ca} - p_{sat}}{1.01325}\right) + \frac{1}{2} ln\left(\frac{0.1173(p_{ca} - p_{sat})}{1.01325}\right)\right], \qquad \text{(Eq. 5.8)}$$

$$V_a = \left(-1.618 \times 10^{-5} T_{fc} + 1.618 \times 10^{-2}\right)\left(\frac{p_{O_2}}{0.1173} + p_{sat}\right)^2 + \left(1.8 \times 10^{-4} T_{fc} - 0.166\right)\left(\frac{p_{O_2}}{0.1173} + p_{sat}\right) + \left(-5.8 \times 10^{-4} T_{fc} + 0.5736\right) \qquad \text{(Eq. 5.9)}$$

5.3.2. Ohmic Losses

The Ohmic losses are caused by the combined electrical resistance of various components inside the cell, namely electrode material, electrolyte membrane and various interconnections. This resistance is experienced by the hydrogen ions flowing through the membrane and by electrons moving on the electrode surface. The voltage drop is proportional to the current. The resistance to the flow of protons in the membrane is much more effective than the resistance of the electrodes and bipolar plates. Ohm’s law is employed for calculation of the losses. The Ohmic losses are a linear function of the current. The polarization curve depicts the Ohmic losses as a linear line at intermediate current densities. These losses are less significant at low current densities. The losses are modeled by using Ohm’s law in principle but different methods are introduced to calculate the Ohmic resistance. Correa *et al.* (2004) developed the model for Ohmic losses using ohm’s law as

$$V_{ohm} = iR_m \qquad \text{(Eq. 5.10)}$$

where i is the current density and R_m is the Ohmic resistance. This resistance is dependent of geometry of the membrane, too. The expression for resistivity is given by

$$R_m = \frac{\rho_m \, l}{A} \qquad \text{(Eq. 5.11)}$$

where l is the thickness of membrane and ρ_m is the resistivity which can be modeled as function of current density and temperature. Amphlett and his coworkers (1995) developed an empirical model for calculation of the Ohmic losses which was the function of temperature and current density. Arsie and his coworkers (2007) modeled Ohmic losses using Ohm’s law as well and Ohmic resistance was function of membrane thickness and conductivity. The membrane conductivity is a function of temperature and water activity and is given by

$$\sigma_m = exp\left(300\left(\frac{1}{303} - \frac{1}{T}\right)\right)(0.0051\lambda - 0.00326) \qquad \text{(Eq. 5.12)}$$

The range of value of λ is from 0 to 14 corresponding to 0 to 100% humidity (Pukrushpan *et al.*, 2004).

5.3.3. Concentration Losses

The concentration losses result from the decrease of concentration of hydrogen and oxygen gases at the electrode. The reduction in concentration is the result of a failure to transport sufficient reactants to the electrode surface which is why these losses are also called mass transport losses. The reactant concentrations are same in the manifold and reaction surface of the electrode at no load. As, the current is drawn, the gases have to diffuse into the catalyst layers. This diffusion causes the reduction of concentration at the reaction sites. These losses are incurred at high current densities due to insufficient quantities of the reactant gases. The water is produced at the cathode though electrochemical reaction. This presence of water particularly at high currents causes clogging of catalyst sites and therefore, restricts oxygen access to the reaction site. The mass transport is significant in this regard. Arsie and his coworkers [39] developed the model for concentration losses considering both anode and cathode chambers. They developed polynomial for current densities as functions of pressures at cathode and anode respectively. Boccaletti *et al*. (2006) used the model for concentration losses as exponential function of current density scaled with a constant extracted from experiments. Buasri and her colleagues (2006) formulated the model for concentration losses similar to Boccaletti *et al.* (2006) but the structure of coefficients is different which include load current also. Pukrushpan *et al.* (2004) employed an empirical model for calculation of the concentration losses. The model depends upon partial pressures of the reactant gases, saturation pressure, temperature and current density. The model is given by Pukrushpan *et al.* (2004) and Amphlett *et al.* (1995).

$$V_{conc} = i\left(C_2 \frac{i}{i_{max}}\right)^{C_3} \qquad \text{(Eq. 5.13)}$$

$C_3 = 2, i_{max} = 2.2$

$$C_2 = \begin{cases} \left(7.16 \times 10^{-4} T_{fc} - 0.622\right)\left(\frac{p_{O_2}}{0.1173} + p_{sat}\right) + \left(-1.45 \times 10^{-3} T_{fc} + 1.68\right) & if\ \frac{p_{O_2}}{0.1173} + p_{sat} < 2\ atm \\ \left(8.66 \times 10^{-5} T_{fc} - 0.068\right)\left(\frac{p_{O_2}}{0.1173} + p_{sat}\right) + \left(-1.6 \times 10^{-4} T_{fc} + 0.54\right) & else \end{cases}$$

(Eq. *5.14*)

A. J. del Real and his colleagues (2007) developed an empirical model for calculation of the fuel cell voltage containing all losses. The model is nonlinear algebraic expression which was function of partial pressures of reactant gases, temperature and load current. Arsie and his coworkers (2007) introduced an additional term as a constant voltage drop that accounts for minor losses such as the contact resistance, internal current, and leaks. In order to design the observer, the voltage model can be expressed considering equation (5.14) as follows:

$$V_{fc} = V_{OC} - V_{act} - V_{ohm} - V_{conc}$$

(Eq. *5.15*)

where V_{fc} is the fuel cell output voltage, E is the open circuit voltage, V_{act} is the activation voltage loss, V_{ohm} is the ohmic voltage loss and V_{conc} is the concentration voltage loss.

In order to design the observer, a dynamical voltage model is developed through rigorous mathematical procedure. The model is as follows:

$$\dot{V}_{fc} = \varphi \dot{x}_3 + \phi \dot{x}_4 + \chi \dot{x}_8 + \psi \frac{di}{dt} + t_m \frac{di}{dt} \tilde{\sigma}_m$$

(Eq. *5.16*)

where $\tilde{\sigma}_m = 1\ \ \sigma_m$ and σ_m is the conductivity of membrane against hydrogen ions. The coefficient functions φ, ϕ, χ and ψ are detailed as follows:

$$\varphi = d_6 \frac{T_{fc}}{p_{ca} - p_{sat}} \qquad \text{(Eq. 5.17)}$$

$$\phi = e_3 \frac{T_{fc}}{p_{O_2}} + c_1 T_{fc} p_{O_2} + c_3 T_{fc} p_{sat} - c_5 - c_6 p_{sat} - c_7 T_{fc} + \frac{1}{{i_{max}}^{c_3}}\, i^{c_3+1}\, c_3\ {c_2}^{c_3}\left(m_5 T_{fc} - m_5\right) \qquad \text{(Eq. 5.18)}$$

$$\chi = e_3 \frac{T_{fc}}{p_{H_2}} \qquad \text{(Eq. 5.19)}$$

$$\psi = -c_1 V_a exp(-c_1 i) - \frac{1}{{i_{max}}^{c_3}} {c_2}^{c_3}(c_3 + 1) i^{c_3} \qquad \text{(Eq. 5.20)}$$

The conductivity parameter is to be estimated therefore a slight uncertainty is introduced as under. We get a perturbed voltage model as follows:

$$\dot{V}_{fc} = \varphi \dot{x}_3 + \phi \dot{x}_4 + \chi \dot{x}_8 + \psi \frac{di}{dt} + t_m \frac{di}{dt}(\tilde{\sigma}_m + \Delta\tilde{\sigma}_m) \qquad \text{(Eq. 5.21)}$$

The ultimate task of this work is to calculate the water content parameter λ_m. As the perturbation on conductivity is recovered then the conductivity is updated by correction term$\Delta\tilde{\sigma}_m$. The λ_m can be calculated by following model

The ultimate task of this work is to calculate the water content parameterλ_m. As the perturbation on conductivity is recovered then the conductivity is updated by correction term$\Delta\tilde{\sigma}_m$. The λ_m can be calculated by following model (Springer *et al.*, 1991).

$$\lambda_m = \frac{1}{\Delta\tilde{\sigma}_m\, b_{11} exp\left(b_2\left(\frac{1}{303} - \frac{1}{T_{fc}}\right)\right)} + \frac{b_{12}}{b_{11}} \qquad \text{(Eq. 5.22)}$$

where $\Delta\tilde{\sigma}_m$ is correction term, b_{11} and b_{12} are from the Nafion membrane (Springer *et al.*, 1991) and b_2 is a fitting parameter (Pukrsushpan *et al.*, 2004).

5.4. Higher Order Sliding Mode Observer Design

In this work, a HOSMO is designed on perturbed voltage model assuming that the measurements of inlet manifold pressure, partial pressures of oxygen and hydrogen are known. The observer of inlet manifold pressure is a previous work of the authors (Kazmi and Bhatti, 2011). The partial pressures of reactant gases are assumed to be known. The proposed structure of the observer for sliding mode observation of output voltage of PEM fuel cell system is designed on perturbed model as follows:

$$\dot{\hat{V}}_{fc} = \varphi \dot{x}_3 + \phi \dot{x}_4 + \chi \dot{x}_8 + \psi \frac{di}{dt} + t_m \frac{di}{dt} \tilde{\sigma}_m - \nu \tag{Eq. 5.23}$$

where injector ν contains two terms i.e. discontinuous time derivative and continuous function of sliding surface. The modified switching function is defined as follows:

$$\nu = \nu_1(t) + \nu_2(t) \tag{Eq. 5.24}$$

$$\dot{\nu}_1 = -W sign(s) \tag{Eq. 5.25}$$

$$\nu_2 = \begin{cases} -\lambda \ |s_0|^{\rho} \, sign(s) & |s| > s_0 \\ -\lambda \ |s|^{\rho} \ sign(s) & |\nu| \leq s_0 \end{cases} \tag{Eq. 5.26}$$

The corresponding sufficient conditions for finite time convergence are:

$$W > \frac{\Phi}{\Gamma_{\mathrm{m}}} > 0, \tag{Eq. 5.27}$$

$$\lambda^2 \geq \frac{4\Phi\Gamma_{\mathrm{M}}(\mathrm{W}+\Phi)}{\Gamma_m^3(\mathrm{W}-\Phi)}, \tag{Eq. 5.28}$$

and

$$0 < \rho \leq 1.$$

The values of constants $W = 0.05$, $\lambda = 0.05$, and $\rho = 0.89$.. The variable s denotes the sliding surface i.e. error between measured and estimated voltages. The surface can be expressed as follows:

$$s = V_{fc} - \hat{V}_{fc} \qquad \text{(Eq. } \mathit{5.29}\text{)}$$

The observer has a task to steer its surface to zero. The equation for surface is obtained by subtracting equation (5.23) from equation (5.21) as follows:

$$\dot{s} = -\Delta\tilde{\sigma}_m t_m \frac{di}{dt} + \nu \qquad \text{(Eq. 5.30)}$$

If the observer steers its error to zero then the following relationship can be obtained from equation (5.30) for $s = 0$ and $\dot{s} = 0$

$$\Delta\tilde{\sigma}_m = \frac{\nu}{t_m(\,di \quad dt)} \qquad \text{(Eq. 5.31)}$$

which is employed to recover the perturbation in the conductivity of fuel cells across the membrane. The injector compensates the perturbations or uncertainties in V_{fc}. The stability and convergence analysis of observer are investigated in detail in (Levant, 1993), (Levant, 2007) and (Fridman and Levant, 2002).

5.5. Simulation Results

In this section, the results of simulation are presented by using the figures. The parameters for simulation are based on fuel cell prototype vehicle (Adams *et al*., 200, Pulrushpan *et al*., 2004). The value of water content parameter is estimated online using the proposed observer. The estimated value of parameter lies in the range of 0 to 14. Moreover, the parameter is calculated offline from the model available in the literature (Springer *et al*., 1991). The water content dynamics are analyzed with respect to load current transients. In this way, it is tried to verify the results of estimation of parameter through quantitative and qualitative analysis.

The observer design is tested on simulations for tracking and robustness. The simulations are run with load current having transients at 100 and 200 seconds for 20 seconds each with increasing and decreasing behaviors respectively as shown in Figure 5.3. The automotive fuel cell system experiences numerous and varied power transients therefore current profile is designed in such a way that it depicts real scenario. The compressor motor voltage is kept held at 100 volts in first case whereas in second case it is varied from 100 to 250 volts as shown in the Figure 5.5.

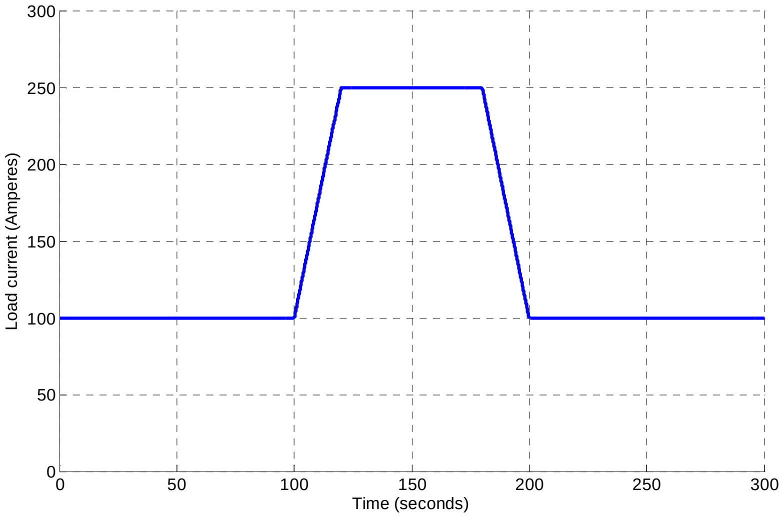


Figure 5.3 Load Current Profile With Transients

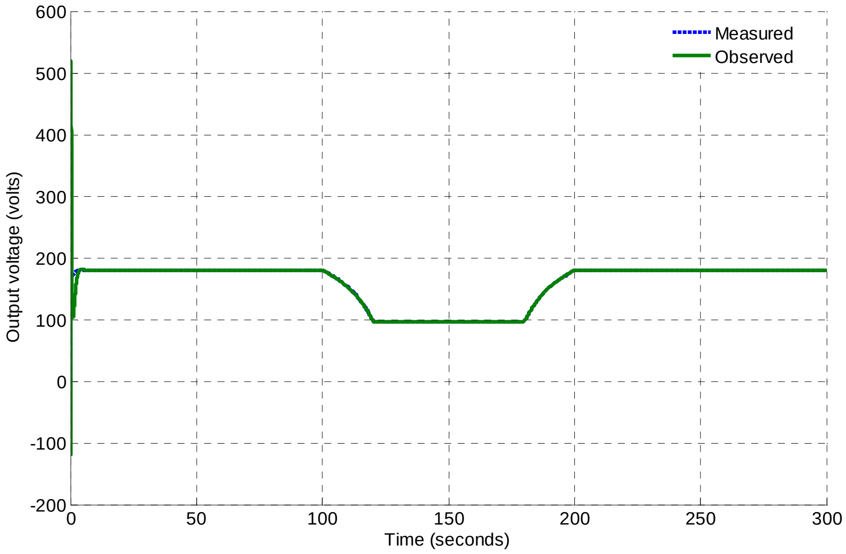


Figure 5.4 Output Voltages of System and Observer

The performance of the proposed observer is shown in the Figure 5.4. The observer tracks the measured voltage under load current transients. The inherent chattering phenomenon of standard sliding mode observer is not obvious in the results. In the second scenario, the performance of observer is very clear from Figure 5.6. No doubt there are over and under shoots but it converges quickly. The results show robustness and fast convergence.

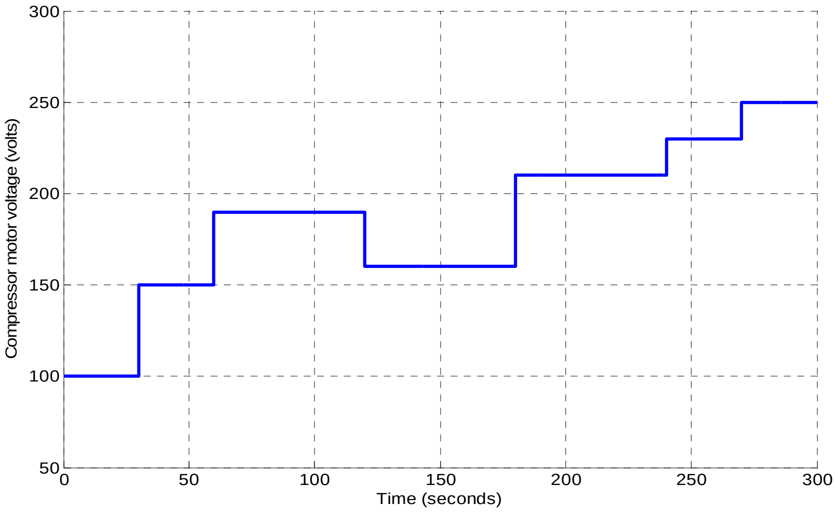


Figure 5.5 Compressor Motor Voltage Profile

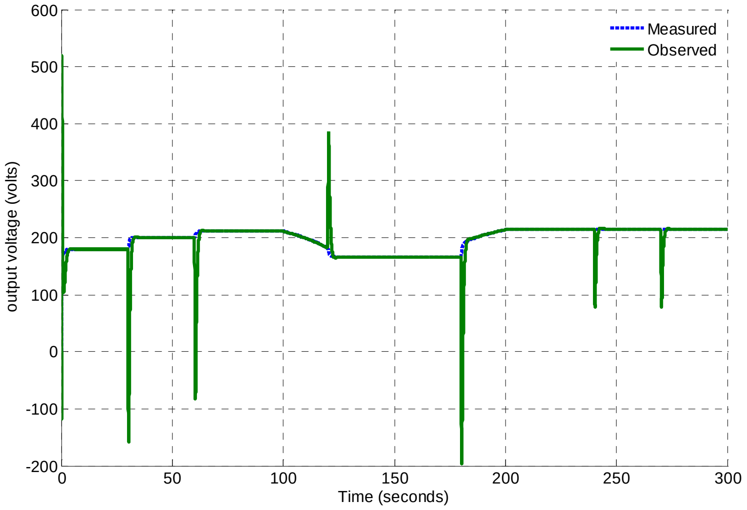


Figure 5.6 Output Voltages of System and Observer under Disturbance

The water content parameter is shown in Figure 5.7. The value of parameter is approximately 12. The value of water content parameter shows that the humidity is 96% approximately.

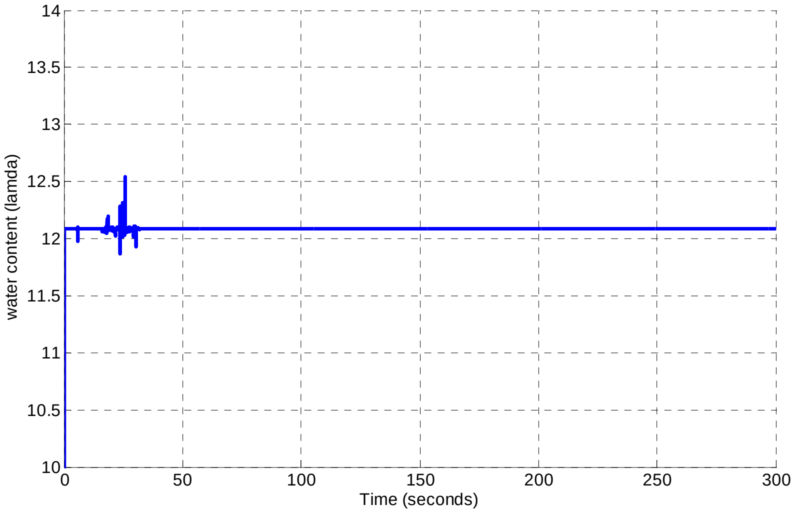


Figure 5.7 Water contents across the membrane of fuel cell

5.6. Validation of Results

The results are verified with test bench simulation model by Pukrushpan *et al.* (2004). Moreover, the value of water content parameter is verified by offline calculation using a model available in the literature.

5.6.1. Quantitative Analysis

The verification of estimates is offline process whereas the parameter estimation via proposed observer is online process. Using ideal gas law, the vapor pressure at cathode is calculated as

$$p_{v,ca} = \frac{R_v T_{st}}{V_{ca}} m_{v,ca,max.} \qquad \text{(Eq. 5.32)}$$

where the value of maximum mass of vapors at cathode side was used as 0.0028 kg (Kunusch *et al*., 2009). The water activity was found by using the vapor pressure and saturated vapor pressure at stack temperature as follows:

$$a_{ca} = \frac{p_{v,ca}}{p_{sat}(T_{st})} \qquad \text{(Eq. 5.33)}$$

Finally a third order polynomial (Springer *et al*., 1991) was used to calculate the value of water content parameter. The model is quit reliable and consistently employed for calculation of the parameter as it is reported in literature recently (Gao *et al*., 2010).

$$\lambda_{ca} = \begin{cases} 0.043 + 17.8a_{ca} - 39.85a_{ca}^2 + 36a_{ca}^3 & 0 < a_{ca} \leq 1 \\ 14 + 1.4(a_{ca} - 1) & 1 < a_{ca} \leq 3 \end{cases} \qquad \text{(Eq. 5.34)}$$

where water activity $a_{ca}$was found less than unity therefore first part of equation (5.34) was used to obtain the value of water content parameter. The difference is less than 5% and therefore simulation results are quite reasonable and compatible. The comparison of online and offline results is shown in the Table 5.1.

Description	**Online estimated value of water content parameter**	**Offline calculated value of water content parameter**	**Difference**
Value	12.0845	12.6501	0.5656

Table 5.1: Comparison of water content parameter

5.6.2. Qualitative Analysis

In the load current profile from 100 seconds to 120 seconds and from 180 seconds to 200 seconds, there are increasing slope and decreasing slop respectively as shown in Figure 5.3. The change in load current affects the water content parameter. As the load current increases, there is dryness process across the membrane. When the load current decreases the wetting process occurs. In practical the dryness process is slow and wetting process is fast. These dynamics can be viewed in Figure 5.8 that contains zoom view of Figure 5.7 from 80 seconds to 220 seconds.

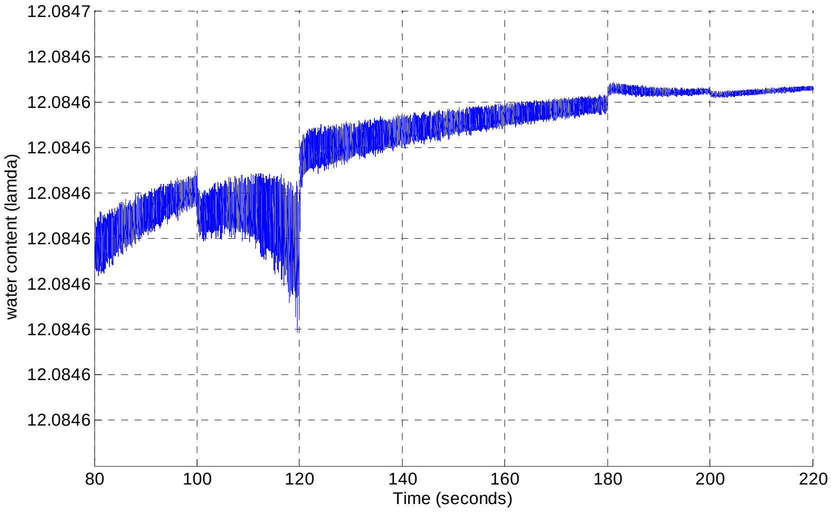


Figure 5.8 Water Content Behaviors under Load Transients

5.7. Summary

Higher order sliding mode observer-based online estimation of water contents across the membrane of fuel cell system (FCS) is presented. The work employs dynamic voltage model developed by authors using basic nonlinear algebraic equations. The model supports sliding mode observation of water content parameter. The standard sliding mode observer (SMO) results inherit chattering phenomena that limits implementation of algorithm therefore, higher order sliding modes enhanced the results of standard SMO through mitigation of chattering effects preserving robustness and fast convergence of SMO. The estimates are quite similar to nominal values. Offline calculation of the parameter through a model available in the literature verifies the results. The observer can replace the humidity sensors which results in rid of expensive and hard measuring instrumentation despite cheaper measurement of output voltage of FCS. The parameter estimation can provide a foundation for design of efficient fault diagnostic schemes and fault tolerant control.

Chapter 6

HIGHER-ORDER SLIDIGN MODE OBSERVER-BASED FAULT DIAGNOSIS IN PEM FUEL CELL SYSTEM

A discrepancy between the actual behavior and the model indicates faults. In the scenario of model mismatch or measurement noises, false alarm can be occurred. Therefore fault diagnostic technique should be capable to reject the false alarms. A robust technique can overcome the false alarms in the presence of disturbances and uncertainties. Higher order sliding mode technique is robust and capable to reject disturbances and uncertainties successfully without losing accuracy and convergence. It was experienced in the mass flow rate and water content estimation process, explained in the last two chapters.

6.1. Future Work

The future work comprises of fault diagnosis in PEM fuel cell system based on higher order sliding modes observers. The two parameters have been estimated using higher order sliding modes observers. The fault diagnosis will be done on the basis of these estimated parameters. The future work comprises:

i) Investigation in the following:
  - Fault diagnostic fundamentals
  - Fault diagnostic techniques
  - Model based fault diagnostic techniques
  - Observer based FDI
  - Higher order sliding mode observer based FDI technique

ii) Modeling of faults in PEM fuel cell system
  - Air leakage in the manifold
  - Hydrogen leakage in the manifold

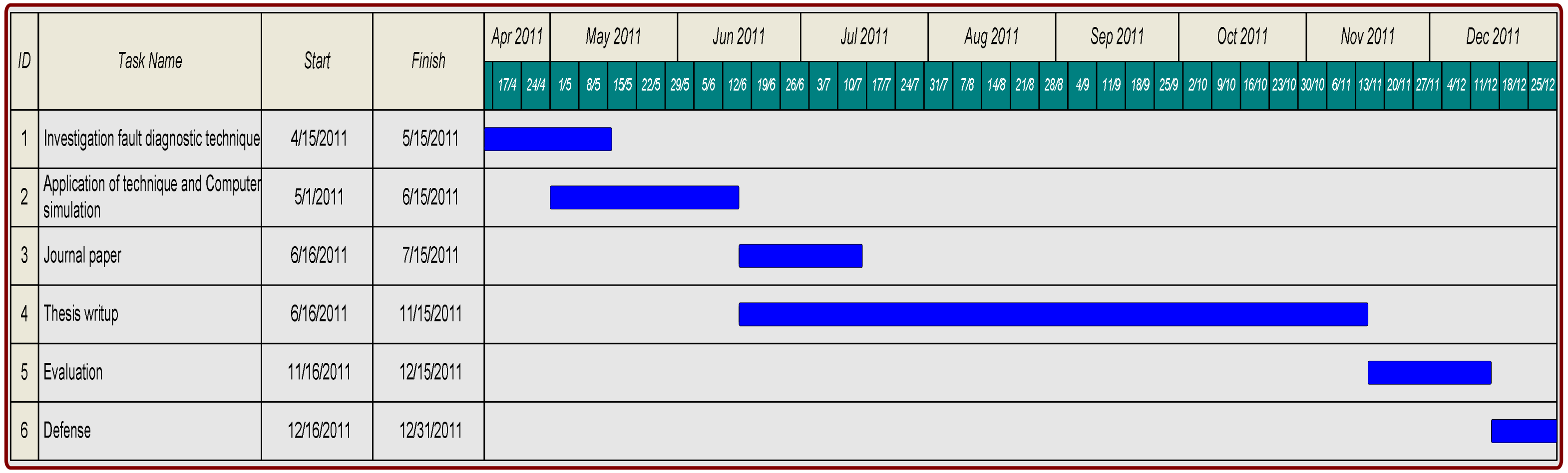
    - Compressor faults
    - Sensor faults
    - Oxygen starvation
    - Fuel starvation
    - Cathode/ anode flooding
    - Cathode /anode drying

iii) Application of fault diagnostic technique

iv) Computer simulation and analysis

6.2. Time line

The six tasks of timeline are investigation in fault diagnostic technique, Application of technique and simulation, Journal paper, Thesis writ up, its evaluation and finally defense of thesis. The timeline via Gantt chart is shown in Figure 6.1.



ID	Task Name	Start	Finish
1	Investigation fault diagnostic technique	4/15/2011	5/15/2011
2	Application of technique and Computer simulation	5/1/2011	6/15/2011
3	Journal paper	6/16/2011	7/15/2011
4	Thesis writup	6/16/2011	11/15/2011
5	Evaluation	11/16/2011	12/15/2011
6	Defense	12/16/2011	12/31/2011

Figure 6.1. Timeline of PhD research work

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