

Modelling and Simulation of Fuel Cell based DC Microgrid

*Dissertation Submitted in partial fulfillment of the requirement for the
award of the degree of*

Master of Engineering *in* POWER SYSTEMS

Submitted By

Deepak Pardeep Malhotra

Regd. No. 801241006

Under the supervision of

Dr. Prasenjit Basak

Assistant Professor, EIED



ELECTRICAL AND INSTRUMENTATION ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

PATIALA (PUNJAB)-147004


JULY-2014

CERTIFICATE

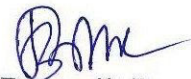
I hereby certify that the work which is being presented in the dissertation entitled '**Modelling and Simulation of Fuel Cell based DC Microgrid**' in partial fulfillment of requirement for the award of the master degree in Power Systems submitted in the Electrical and Instrumentation Engineering Department, Thapar University, Patiala is an authentic record of my own work carried out under the guidance of **Dr. Prasenjit Basak**, (Assistant Professor EIED, Thapar University, Patiala).


The matter presented in this dissertation has not been submitted for the award of any other degree of this or any other university.


Date: 15-7-14


Deepak Pardeep Malhotra
801241006

This is to certify that the above statement made by the candidate is correct and true of the best of my knowledge & belief.


Dr. Prasenjit Basak
Assistant Professor
Electrical & Instrumentation Engg. Department
Thapar University, Patiala

Countersigned by: 
(Dr. Ravinder Aggarwal)
Professor & Head
Electrical & Instrumentation Engg. Department
Thapar University, Patiala


(Dr. S.K. Mohapatra)
Sr. Professor & Dean (Academic Affairs)
Thapar University, Patiala

ACKNOWLEDGEMENT

I would like to thank Thapar University for giving me the opportunity to use their resources and work in a challenging environment.

First and foremost, I take this opportunity to express my deepest sense of gratitude to my guide **Dr. Prasenjit Basak**, Assistant Professor, Thapar University, Patiala for his able guidance during my dissertation. This dissertation would not have been possible without his help and the valuable time that he has given me amidst of his busy schedule.

I would like to express my deep sense of gratitude towards **Dr. Ravinder Aggarwal**, Professor and Head, **Ms. Manbir Kaur**, Associate Professor (P. G. Coordinator), EIED, Thapar University, Patiala who has been a constant source of inspiration for me throughout this dissertation.

I would also like to extend my gratitude to my parents, friends and senior students of this department who have always encouraged and supported me in doing my work.

Last but not the least I would like to thank to all the staff members of the Department of Electrical & Instrumentation Engineering who have been very cooperative with me.



Deepak Pardeep Malhotra

Regd. No.801241006

Abstract

In the modern power scenario the deployment of distributed energy resources are gradually increasing day by day to find out the most suitable alternatives from the several choices of DERs. The natural uncertainty is inevitable in renewable energy resources such as solar and wind energy based systems. In this perspective, the Fuel Cell technology is considered as one of the promising DER which is almost free from the effect of climatic conditions. In this context, this dissertation presents a detailed literature survey on fuel cell technology and its promising applications in microgrid. This research proposes a model of Fuel Cell based DC microgrid supplying resistive loads and rotational machines such as separately excited DC motor using Matlab/Simulink software. This proposed model has the feature of critical and non-critical load selectivity which is an important property of microgrid. In addition, this work shows the scopes of future research on Fuel Cell based microgrid aiming maximum utilization of this technology as a part of solution to energy crisis in the near future.

Table of Contents

Certificate	i
Acknowledgement	ii
Abstract	iii
Table of contents	iv-v
List of Figures	vi
List of Tables	vii
List of Acronyms	viii

Chapter1. Introduction

1.1 Overview.....	1
1.2 Motivation.....	2
1.3 Objective of the work.....	2
1.4 Organization of dissertation.....	3

Chapter2. Comprehensive Literature Survey on Fuel Cell Technology and its Application in Microgrid

2.1 Introduction.....	4
2.2 Fuel cell Architecture.....	5
2.3 Comparison of different Fuel cells.....	7
2.3.1 Proton Exchange Membrane Fuel cell.....	8
2.3.2 Alkaline Fuel cell.....	9
2.3.3 Molten Carbonate Fuel cell.....	10
2.3.4 Solid oxide Fuel cell.....	11
2.4 Fuel Cell Applications.....	13
2.5 Cogeneration.....	14
2.6 Hydrogen Production and Storage.....	15
2.7 Fuel Cell based Microgrid.....	16
2.8 Inference.....	18

Chapter3. Modeling and Simulation of a Fuel Cell system Supplying Power to a separately excited DC Motor

3.1 Introduction.....	19
3.2 Modeling and Simulation of a fuel cell system.....	19

3.3 Study on variation of load torque of a separately excited DC motor.....	21
3.3.1 Model description.....	22
3.3.2 Modelling of DC-DC Converter	22
3.3.3. Modelling of separately excited DC Motor.....	23
3.3.4. Mechanism of fuel flow rate regulator.....	24
3.3.5 Simulation of FC supplying Power to DC Motor.....	25
3.3.6 Inference.....	28
Chapter 4 Performance Analysis of Proposed Fuel cell based DC Microgrid	
4.1 Introduction.....	29
4.2 Simulation of proposed FC based microgrid supplying power to DC motor.....	30
4.2.1. Model Description.....	30
4.2.2 Simulation and results.....	30
4.2.3. Waveforms.....	31
4.3 Microgrid supplying Power to Critical and Non -critical load.....	33
4.3.1. Model Description.....	33
4.3.2. Simulation of a FC based MG supplying Power to critical and Non- Critical Load.....	33
4.3.3 Waveforms.....	34
Chapter5. Conclusions and Future Scope of Work	
5.1 Conclusions.....	37
5.2 Future scope of Work.....	37
References.....	38

List of Figures

Figure 2.1	Construction of a typical Fuel cell.....	8
Figure 2.2	Various Types of Fuel Cells.....	12
Figure 3.1	Fuel cell system supplying power to resistive load.....	20
Figure 3.2	Fuel flow rate.....	20
Figure 3.3	Fuel cell Voltage.....	21
Figure 3.4	Fuel cell Current.....	21
Figure 3.5	Fuel cell supplying Power to DC Motor.....	21
Figure 3.6	Simulink model of DC-DC Boost Converter.....	22
Figure 3.7	Simulink model of separately excited DC motor.....	23
Figure 3.8	Simulink model of three point Starter.....	24
Figure 3.9	Fuel flow rate.....	25
Figure 3.10	Fuel cell Voltage.....	25
Figure 3.11	Fuel cell Current.....	26
Figure 3.12	Fuel cell Efficiency.....	26
Figure 3.13	Speed of DC Motor connected to Fuel cell.....	26
Figure 3.14	Motor Torque when connected to Fuel cell.....	27
Figure 3.15	Motor Power to when connected to Fuel cell.....	27
Figure 3.16	Motor Armature Current when connected to Fuel cell.....	27
Figure 4.1	Fuel cell based Microgrid supplying Power to DC Motor.....	30
Figure 4.2	Power Supplied by Fuel Cell to the DC Motor.....	31
Figure 4.3	Power Supplied by Battery Bank to the DC Motor.....	31
Figure 4.4	Power Supplied by Grid to the DC Motor.....	32
Figure 4.5	Motor Output Power.....	32
Figure 4.6	FC based Microgrid Supplying Power to Critical and Non-Critical load.....	33
Figure 4.7	Power Supplied by Fuel cell to the Load.....	34
Figure 4.8	Power Supplied by Battery bank to the Load.....	34
Figure 4.9	Power Supplied by Grid to the Load.....	35
Figure 4.10	Total Power Supplied to Critical Load.....	35
Figure 4.11	Total Power Supplied to Non-Critical Load.....	35

List of Tables

Table 2.1 Different type of Proton Exchange Membranes.....	9
Table 2.2 Different type of fuel cells and their comparison.....	13
Table 2.3 some major developers of fuel cells.....	16
Table 4.1 Current distributions of various Power sources and load.....	32
Table 4.2 Power distributions of various Power sources and load.....	32
Table 4.3 Current distributions of various Power sources and load.....	36
Table 4.4 Power distributions of various Power sources and load.....	36

List of Acronyms

DER.....	Distributed Energy Resource
FC.....	Fuel Cell
PEMFC.....	Proton Exchange Membrane Fuel Cell
SOFC.....	Solid Oxide Fuel Cell
AFC.....	Alkaline Fuel Cell
MCFC.....	Molten Carbonate Fuel Cell
PV.....	Photo Voltaic
PCC.....	Point of Common Coupling
ORR.....	Oxidation Reduction Reaction
PSA.....	Polystyrene Sulfonic Acid
FEN.....	Fuel Cell Energy Network
GA.....	Genetic Algorithm
CFC.....	Chloro Fluro Carbon
HCFC.....	Hydro Chloro Fluro Carbon
MPPT.....	Maximum Power Point Tracking
IDN.....	Islanded Distribution Network
EMS.....	Energy Management System
SCADA.....	Supervisory Control and Data Acquisition
SST.....	Solid State Transformer
SOC.....	State of Charge

Chapter 1

Introduction

1.1 Overview on Application of Fuel cell

The demand of energy is increasing day by day due to rising population and improvement in standard of living, particularly in developing countries like India. Still a large population living in remote areas has no access to electricity. In 2012 around 1.3 billion people around the world did not had access to electricity. Two third of this population was living in rural areas of Asia and Africa [1]. The dependence on technology in daily living is increasing per capita power consumption in urban areas. This is a cause of concern as increase in power generation will result in rise in fossil fuel consumption and pollution. Also fossil fuels are depleting very rapidly, so there are urgent need for the world to switch to renewable sources of energy which can be used again and again [2].

Besides the advantage of being non- polluting, renewable sources can be used as distributed sources of energy as they can be installed anywhere depending on the availability of renewable energy. The distributed energy resources (DER) include wind energy, solar energy, biomass, geothermal, fuel cell etc. out of the entire DER, fuel cells have the advantage that they can be installed in the remote areas as well as inside residential and commercial buildings. Their only requirement is the constant supply of hydrogen as a fuel. Earth receives abundant supply of solar energy from the sun. Around 3.78×10^{24} joule of energy is received by earth every year which is equivalent to energy from 1.3×10^6 billion ton of standard coal. The use of other type of renewable energy resources like wind, geothermal, tidal etc. are subjected to their availability. Fuel cells have higher potential in terms of efficiency and can transfer higher amount of power in comparison with batteries [3].

The DERs are seen as possible solution to ever increasing demand for electricity and also for the sustainable development of power generation. The problem with the use of solar energy, wind and geo thermal energy for power generation is changing weather conditions and high installation cost. Many innovations are going on to improve DER technology for commercial power generation. This includes the use of Fuel cells along with other DER like battery bank, super-capacitors as hybrid power generation.

1.2 Motivation

In order to achieve complete rural electrification and reliable power, commercial development of non conventional resources such as fuel cell is necessary. The fuel cell is a clean source of energy as it uses hydrogen as a fuel. These can be installed anywhere as long as constant supply of fuel can be made available in that area. Most of the research work in the fuel cell is focused on fuel cell supplying dc motors for electric vehicle and less research work has been done in the field of fuel cell supplying energy to rotational machines. So to analyze the effect of changing load torque on the output of fuel cell and its internal parameters a simulation model is studied to observe the performance of the fuel cell system while supplying a DC motor. Also to study the power sharing between fuel cell, battery and a DC grid, a low voltage DC microgrid is modeled and simulated using Matlab/Simulink.

1.3 Objective of work

The objective of this dissertation is to study the dynamic performance of PEM fuel cell when connected to rotational machines like dc motor through modelling and simulation using Matlab/Simulink. The variation of motor parameters like speed, torque is investigated. The work has also been done to explore response of fuel cell to changing parameters like fuel flow rate keeping the other fuel cell parameters like system temperature, air flow rate, air pressure, hydrogen utilization and oxygen utilization constant.

The objectives of the dissertation are stated below:

- (a) To perform a comprehensive literature survey on the aspect of fuel cell technology to be implemented in the emerging microgrid system.
- (b) To study the performance of PEM fuel cell supplying a resistive load through modeling and simulation using Simpower in Simulink/Matlab.
- (c) To study the performance of PEM fuel cell supplying a separately excited DC motor and validating the simulation results through mathematical equations related with the performance of separately excited DC motor.
- (d) To propose a fuel cell based DC microgrid system catering a separately excited DC motor as a load connected with the composite system.
- (e) To analyze the grid connected and islanded mode operation of the proposed fuel cell based DC microgrid system.

(f) To explore the scopes of future research based on the work presented in the Dissertation focusing fuel cell based microgrid system.

1.4. Organization of the dissertation

The dissertation is organized in five chapters to present the outcomes of the research work to meet the above mentioned objectives. A comprehensive literature survey based on fuel cell technology as implemented in the microgrid system is presented in the Chapter 2. In chapter 3, a fuel cell system is modeled and simulated using Simulink-Matlab software to study effect of variation in fuel flow rate on stack voltage and efficiency of fuel cell when a resistive load and a DC motor is connected across it separately. An autonomous Fuel Cell based DC microgrid system is proposed and its operation in grid connected mode and islanded mode is studied in Chapter 4. The conclusion of this dissertation along with future scopes of research is presented in Chapter 5.

Chapter 2

Comprehensive Literature Survey on Fuel Cell Technology and its Application in Microgrid

2.1. Introduction

A fuel cell is an electrochemical device that produces electric power in the form of direct current by converting chemical energy present in the fuel (hydrogen). William Grove of United Kingdom and Friedrich Schoenbein of Switzerland were among the first who pioneered the work in the field of Fuel Cell in 1830s. General electrical of the united states was the first to develop the Proton exchange membrane fuel cell(PEMFC) for the use of National Aeronautics and Space Administration (NASA) in 1960s for their first manned space vehicle Gemini. Several companies are developing PEMFC technology for space power applications. Ballard power system was one of the first power companies that pioneered in the field of fuel cells for military application. Ballard started making power system for military application that would run longer and virtually silent as compared to other sources of power. Preferably hydrogen is used as a fuel and oxygen is used as an oxidant for Fuel Cells. Although air can be used instead of oxygen but there is decrease in the Fuel Cell efficiency for this kind of arrangement [2].

The concept of microgrid system as found in several literatures is presented here. Since a large population on earth does not have access to electricity and most of this population lives in rural and remote areas, the distribution generation technology is one of the most effective ways to eradicate the power deficiency in these areas [4]. The DERs consist of a variety of generation technologies such as fuel cells, solar, micro-turbines and wind etc. and the main advantage is that there is reduction in the transmission distance and hence the cost of installation and maintenance of transmission infrastructure is very much reduced [5]. A microgrid is a power system consisting mainly of distributed energy resources, interconnected loads and capable of operating in grid connected as well as islanded mode including critical and non-critical load selectivity [6]. As mentioned in [7] the centralized model of generation, transmission and distribution has become outdated and less efficient due to high transmission and distribution loss. The existing high voltage transmission of power is controllable and reliable but it has the problem of complexity in interconnected grid system which requires control system for reliable operation. The conventional generating power

systems which comprise of large generating units are less flexible to the ever increasing load demand. Any problem in one grid can have cascading effect on other grids. This has given way to more efficient, environment friendly microgrids. The developments in the field of microgrids include increase penetration levels of distributed energy resources (DER), improved generation efficiency through use of CCHP (combined cooling heat and power). Again as mentioned in [7], for the effective operation of microgrid the different typed of distributed energy resources that are connected with each other must be provided with various electronic interfaces. These electronic interfaces makes microgrid more flexible in case of fault as well as load variations. This increases the reliability and flexibility of the microgrid. Microgrid either operates in grid connected mode or in islanded mode. In grid connected mode voltage and frequency parameters of microgrid are controlled by main grid but controlling operation in islanded mode is quite complicated due to less storage capacity and lack of inertia because of increasing penetration of DER units. Also there is natural uncertainty in various DER technologies like wind, photovoltaic etc. [8, 9].

It was observed in [10], while operating in grid connected mode any fault arising in utility grid will result in large fault current in microgrid. This can be overcome using traditional over current relay. However the use of multiple DER inherently producing D.C electric power and then converting it into A.C electric power using semiconductor devices introduces complications in the protection scheme of microgrid as fault current in case of grid independent mode may not rise to a value to use traditional over current protection techniques. As traditional protection equipments are based on the principle of current sensing, the lower values of fault current in case of inverter interfaced distributed generation makes traditional over current protection schemes non effective.

Also it was mentioned in [11] that the presence of multiple distribution generators in case of microgrid makes power and fault current non unidirectional. The conventional protection schemes are made for unidirectional power flow. So this is a hindrance to selection of conventional protection schemes for microgrid.

2.2. Fuel cell architecture

There are many types of Fuel cell line PEMFC, MCFC, AFC, SOFC. But only PEMFC can be operated at normal air temperature. PEMFC is lightweight so it can be easily transported, used for distribution power generation. There are a number of fuel cells that can be chosen according to the power rating. 1kW FC has the output voltage range of about 25-50 V and 30

kW and above Fuel cells have output voltage of about 200-400V [12]. As stated in [13], a fuel cell system has five basic sub systems these include fuel processor, water management, air management, thermal management and power conditioning sub system. These are briefly discussed in the following subsections:

(a) Fuel Processor: As hydrogen is the most preferred fuel for the fuel cells, so a fuel processor is used to produce hydrogen from various sources like hydrocarbons. But storing and transportation of high pressure hydrogen remain the issues in implementation of fuel cell technology [14]. The nature of fuel processor depends on the type of fuel cell used. As mentioned above PEMFC is a low temperature fuel cell, therefore a relatively complex fuel processor is used which includes a desulfurizer and a gas cleanup system for the removal of CO (carbon monoxide). For the fuel cells operating at higher temperature like MCFC and SOFC preheating of fuel is required before it is injected into the fuel cell. Therefore fuel processor for such types of fuel cells contains desulfurizer as well as pre heater.

(b) Air management: For the oxidation of fuel, the fuel cell requires air as the oxidant. So air management is a very important aspect of fuel cell system. Either blower or air compressor is used for the providing air to the fuel cell. The choice of using either blower or air compressor depends on whether to give low pressure air or a high pressure air to the fuel cell. The main advantage of giving high pressure air to the fuel cell is that it increases that stack efficiency and improves the electrochemical reactions kinetics. In [15], an ultra high speed compressor was used for better air management of fuel cell. The centrifugal compressors are compact in size and have advantage of low noise pollution. However increasing the air pressure has some disadvantages like it decreases the capacity of air to hold water thus affecting the humidification processes of the fuel cell. Also the power required for compressing the air to high pressure is derived from the fuel cell itself. Thus power required by air compressor is more than any of the other auxiliary devices that are connected with the fuel cell.

(c) Water management: As mentioned in [16], the removal of water from cathode of lower operating temperature fuel cells like PEMFC is a major challenge. The common practice is to purge the cathode flow fields. A flow field tapered channel is presented which separates water produced from the air flow that is needed for fuel oxidation. Water is produced as a byproduct in the electrochemical reactions that undertake place inside the fuel cell. This means even in case where large amount of water is produced, the air management of fuel cell

does not get affected. Water is required for a variety of applications in the fuel cell. In the fuel processor water is required to react with hydrocarbons for the steam reforming reactions. Moreover in the PEMFC pre humidification of reactant gases is required to prevent the drying of fuel cell membrane. For the automotive applications it is very important that water produced in the fuel cell is sufficient for humidification of reactants. If water produced is not sufficient then it must be externally added for the reactant humidification.

(d) Thermal management: Thermal energy released by the fuel cell depends upon the output power of the fuel cell. This thermal energy can be used for a variety of applications including cogeneration. Low temperature fuel cells require air to be flown through cathode to drive out the excess heat. In high temperature fuel cells like MCFC and SOFC the excess heat is removed by liquid coolant. However in this case the thermal energy generated by the fuel cell is used to pre heat the reactant gases and fuel reforming in the fuel processor. Extra heat generated by the fuel cell can be used for cogeneration. Therefore fuel cells must be properly integrated for the optimal use of the thermal energy of the fuel cell.

(e) Power Management: The output of the fuel cell is dc. The direct current produced by the fuel cell at a voltage varies with the change in load. Therefore a dc-dc converter is required for the protection of fuel cell from overvoltage and over current originating with the load variations. For the AC load an inverter is required for transforming DC output to AC. Again as the response of fuel cell is slow to the load variations so a battery or super capacitor is required for supplying the initial power to the load. As mentioned in [12] as the load changes, there is increase in the inrush current to the battery or the super capacitor. Therefore to protect the storage device it is important to use bi-directional converter. The bi-directional converter protects the storage device by controlling the charge and discharge current.

2.3. Comparison of different types of fuel cells

As explained in [17] PAFC technology is commercially available as well as technologically more advanced in comparison with other type of fuel cells. MCFC still needs some improvement to overcome technical and economical barriers before they could be commercialized at par with other type of fuel cells. SOFC is very useful particularly in stationary fuel cell. They are very much commercialized. If economic issues are resolved then SOFC can be very successful in distributed generation applications. PEMFC have become very popular in the recent years due to technological breakthroughs in the field of cell power density as well as reduction in the cost. These are the only type of fuel cells which

are being tested for the vehicular applications. Brief analysis of various types of fuel cells is stated below:

2.3.1. Proton Exchange Membrane Fuel Cell

As shown in the figure 1 the fuel cell consists of a porous Anode, cathode and a proton conducting membrane. The fuel, usually hydrogen is oxidized at anode. The oxidation reaction produces electrons which travel through the external circuit. This reaction also produces protons which travel through the electrolyte to reach cathode. At cathode these electrons and protons react with oxygen to produce water. The membrane acts as a separator between hydrogen and fuel and also provides conducting path for the protons to travel to cathode for oxidation. The two half cell reactions that occur in the fuel cell are [2]:

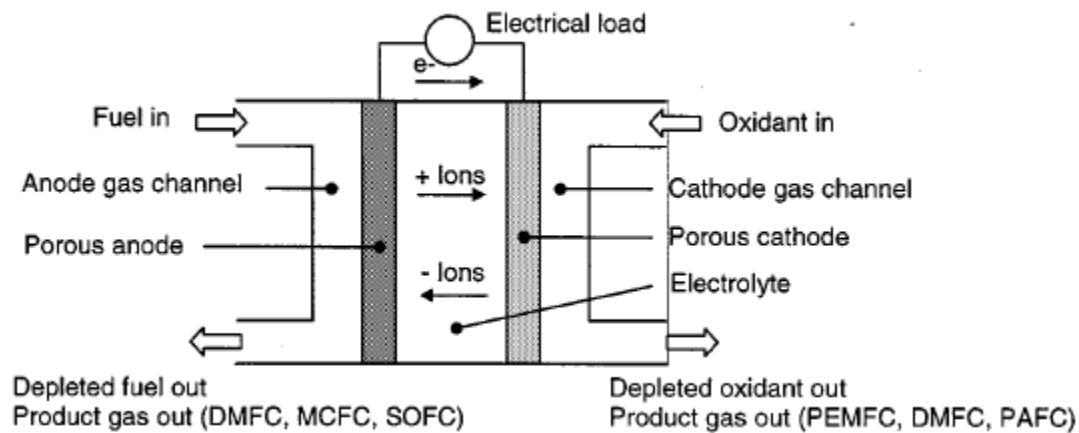


Figure 2.1 Construction of a typical Fuel cell [13]

As mentioned in [2], the proton exchange membrane has good ionic conductivity. Gas permeability is low. It is resistant to swelling and has high chemical stability. For most of the early history of fuel cells ionomer Nafion was used as the membrane material for the PEMFC several other materials that have been used for the proton exchange membrane are shown in the table below. Earlier NASA fuel cells were equipped with Polystyrene Sulfonic Acid (PSA).

Table 2.1
Different type of Proton Exchange Membranes [2]

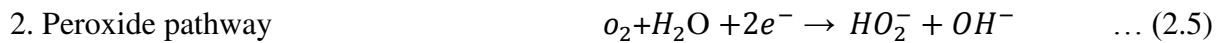
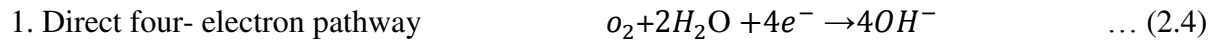
Year	Membrane	Lifetime (thousands of hours)
1959-1961	Phenol Sulfonic Acid	0.3-1
1962-1965	Polystyrene Sulfonic Acid	0.3-2
1966-1967	Polytrifluorostyrene Sulfonic	1-10
1968-1970	Nafion experimental	1-100
1971-1980	Nafion production	10-1000

2.3.2. Alkaline Fuel cell

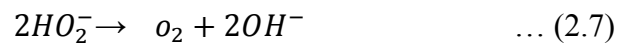
As far as the delivery of significant power is concerned alkaline fuel cells were the first practically working fuel cell. Alkaline fuel cells are efficient and can operate under wide range of temperature. AFC use potassium hydroxide (KOH) as the electrolyte. As mentioned in [2] the pioneering work in the development of AFC was done by Francis Thomas Bacon. Prior to the development of PEMFC, AFC were actively used by NASA.

The main problem with the early AFC was the liquid electrolyte management. The liquid electrolyte was difficult to immobilize. Also there was problem related carbon dioxide absorption from the ambient air. The AFC have a wide range operating temperature. These can be operated at low temperature of 70 degree Celsius to higher temperature of 250 degree Celsius. However for a temperature above 100 degree Celsius, a pressurized system is required to prevent the electrolyte from boiling. PEMFC cannot be operated at this temperature range because the high temperature will degrade the membrane of the fuel cell. For the alkaline fuel cell potassium hydroxide is used as the electrolyte. The potassium hydroxide acts as hydroxide ion conductor. As shown in the equation 2.4 to 2.7 at the cathode oxygen reduction reaction take place (ORR). The ORR produces hydroxide ions that travel through the electrolyte to the anode. At anode the hydrogen oxidation reaction takes place where the hydroxide ions are used to produce water as the byproduct. In a continuous process some of the water formed diffuses to cathode and reacts with oxygen to form hydroxyl ions. As mentioned in [18, 2], the alkaline fuel cell offers advantage of producing high voltages at comparable current densities. The cost of catalyst and membranes is cheaper as compared to other type of Fuel cell. AFC can operate at higher thermodynamic efficiency and have longer cell life. Their Hydrogen purity is not a very important factor for efficient cell operation. Also

choice of possible catalyst is wider. Most of the polarization losses occur at cathode because oxidation reduction reaction is a very sluggish reaction as compared to hydrogen oxidation reaction occurring at the anode. Alkaline fuel cell can have a maximum efficiency of 60 % .this is because the oxidation reduction reaction in case of AFC is more facile in alkaline media as compared to acidic media. Due to facile ORR higher voltages can be obtained in AFC at a given current. The ORR is complex reaction involving four steps as mentioned in [2].



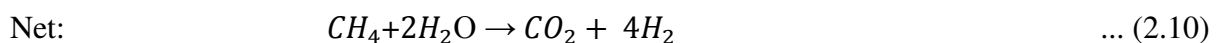
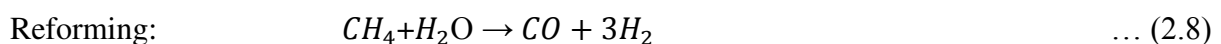
The peroxide (HO_2^-) produced undergoes decomposition resulting in the formation of dioxygen and OH^-



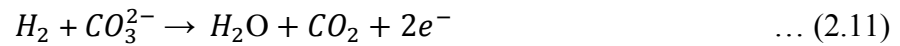
2.3.3. Molten carbonate Fuel Cell

These are the earliest fuel cells which can be operated at higher temperature and with a variety of fuels with lower emissions. As mentioned in [13], the MCFC consist of nickel and nickel-oxide electrodes and molten carbonate as the electrolyte. It also consists of cell separator and collector plates. A separate cooling system is not required in MCFC as heat produced inside the fuel cell is transferred to the reactant and product gases. As mentioned above MCFC operate at very high temperature (650 degree Celsius) so heat produced from the stack can be utilized for cogeneration applications.

As mentioned in [19], two porous electrodes are used and are placed in ceramics matrix filled with molten carbonate as the electrolyte. Hydrogen is the fuel used in the MCFC and it is derived from the natural gas the various chemical reactions used in the MCFC are mentioned below [2]:



At anode hydrogen formed in the reforming reaction reacts with carbonate ion to produce water and carbon dioxide. The chemical reaction illustrating this is shown below:



The carbon dioxide produced at the anode for the cathode reaction to take place. The cathode reaction is shown below:



The carbonate ions produced at the cathode travel to anode where they are used in the anode reaction. Some advantages of MCFC are higher electrical efficiency due to decrease in fuel cost / KWH generated. Reduced carbon footprint / KWH and low noise is generated and due to high operating temperature waste heat generated could be used for cogeneration.

2.3.4. Solid Oxide Fuel Cell

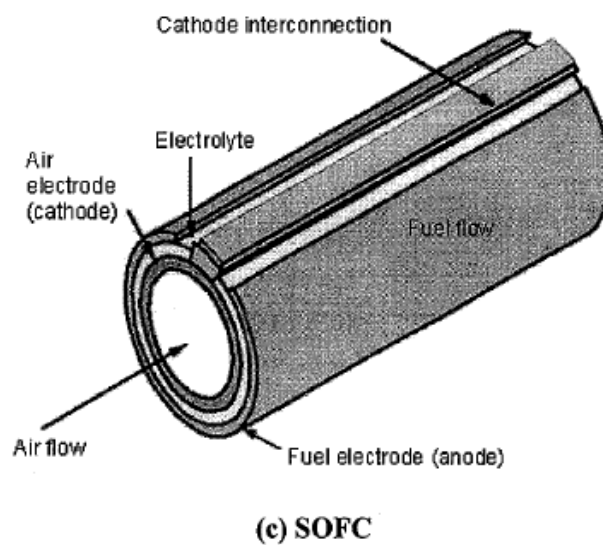
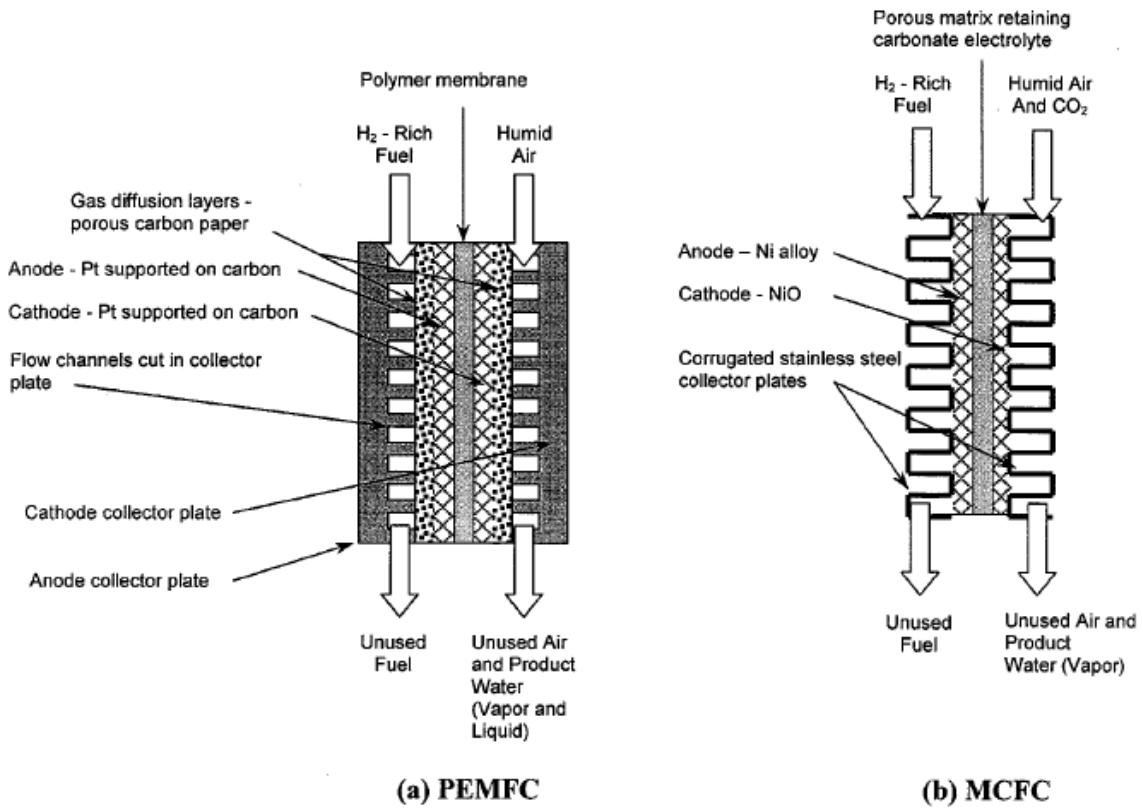
Of the various types of available fuel cell technologies as shown in Fig. 2.2 the solid oxide fuel cells are the best as far as the stationary power production is concerned [20]. The SOFC have high electric efficiency. As the operating temperature of SOFC is quite higher than other type of fuel cells, so their operation is also more complex than other fuel cells. This means that SOFC needs to be heated and kept at their operating temperature. One more thing has to be taken into account that cells of the ceramics should be strong enough to bear the thermal stress originating from the high operating temperature of the SOFC. Moreover SOFC cannot be started or stopped rapidly. So in case of a fluctuating load their reliability is not so good. This feature of SOFC makes it unfit as far as distributed generation is concerned. But for supplying continuous load SOFC are very suitable [21].

As the SOFC operate at such a high temperature, therefore heat released by it can be recovered. Also the SOFC can be integrated with gas powered micro turbines to achieve an overall efficiency of 70% [22]. Various chemical equations are involved in the working of Solid Oxide Fuel cell. Hydrogen as a fuel is fed to the anode and air as the oxidant is supplied to the cathode. As stated in the equation below hydrogen splits into protons and electrons. These electrons travel through the external circuit and react with the oxygen from the air which is fed externally to the cathode. This reaction produces oxygen ion. The oxygen ion reacts with hydrogen to generate heat and water [2].

cathode: $H_2 \rightarrow 2H^+ + 2e^-$... (2.13)

Anode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$ (2.14) ... (2.14)

Overall: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (2.15) ... (2.15)



(c) SOFC
Figure 2.2 Various Types of Fuel Cells [13]

Table 2.2
Different type of fuel cells and their comparison [23].

Fuel cell type	Operating temperature (degree Celsius)	Fuel compatibility	Catalyst	Power range	Applications
PEMFC	60-80	Hydrogen, methanol	Platinum	1W-100kW	Space, Portable Transport, Stationary
AFC	40-60	Hydrogen, methanol	Platinum, Nickel, nickel oxide	1kW-100kW	Space, Portable Transport
MCFC	600-700	Hydrogen, methanol	Nickel	1kW-10MW	Transport Stationary
SOFC	750-1050	Hydrogen, carbon monoxide	Perovskites	500kW-10MW	Transport Stationary

2.4. Fuel Cell Applications

The increasing demand for clean sources of energy due to fast depleting fossil fuels has put use of unconventional sources of energy more in demand. Among the unconventional sources of energy, Fuel Cell is becoming more popular because of virtually silent operation, environment friendly and higher efficiency [24]. Also the hydrogen is used as fuel in the fuel cells which is abundant in the earth and less prone to depletion as compared to other hydrocarbon fuels used for electricity production like diesel, coal, natural gas etc. The application of Fuel Cell can be broadly categorized into three broad areas in [25] as mentioned below:

- Portable power generation.
- Stationary power generation.
- Power for transportation.

As Portable power generator, Fuel Cell are used to charge up movable products as auxiliary power units (APU). Portable fuel cell has longer run time as compared to batteries. Stationary Fuel Cell is not designed to be moved. Their sole purpose is to provide electricity. Stationery Fuel Cells are used as backup power supply system. These include uninterrupted power supply (UPS) and primary power generation. Stationery Fuel Cells are very useful in remote power application like in spacecraft, rural locations and remote research facilities. These Fuel Cells can also be used to provide power to those areas which do not have access to grid like refugee camps after natural or manmade disaster.

Transport Fuel Cell is used to provide propulsive power to vehicles. Fuel cell propelled light duty vehicles (LDV) has seen limited growth but it is the main target for the automakers in 2014[19]. [26] has explained the use of fuel cells in the automotive applications and the drawbacks associated with it. Electric vehicles are particularly used in the mines or indoor areas, where air or noise pollution is prohibited due to health hazards. Fuel cell based electric vehicles can drastically reduce the air pollution as well as dependence on fossil fuels. However there are still some technological barriers such as vehicles with onboard fuel processor need time to produce hydrogen which is not useful for practical applications. Also these fuel processors are not emission free.

2.5. Cogeneration

Cogeneration is the process by which a single power source is used to produce both electricity and heat. This process minimizes the heat wastage from power plants. So the efficiency of the whole generating system is increased. In conventional thermal power plants the conversion rate of primary energy becoming electrical energy is 33%. While in modern combined gas plants it is 55% and using the cogeneration this value becomes 90% [15]. In [27], Fuel Cell Energy Network (FEN) is explained which uses heat available from exhaust. The heat generated from the Fuel Cell is absorbed using hot water piping network. Genetic Algorithm (GA) was used to identify the most preferred path of the hot water piping. In [28] a residential fuel cell cogeneration system was explained. The residential fuel cell cogeneration consists of a Fuel cell stack, a fuel processor to extract hydrogen from natural gas as explained above, a thermal recovery device, hot water tank and a backup auxiliary boiler. The R&D in the Residential fuel cell cogeneration system is very strongly promoted by the private sector especially in Japan. For example Osaka Gas started the research and development of PEFC system since 1999. For the residential fuel cell cogeneration system the excess electricity generated by the fuel cell cannot be sold to power utilities or sent to the grid in certain countries. So the excess electricity is converted to heat energy. In this way heat-electricity ratio is changed to increase the energy savings. In [29] a dc microgrid is proposed for the residential houses where each house uses cogeneration technique. Each house has small distribution generators like fuel cells and the output of these generators is connected to the DC power line. The electricity from the DC power line is given to each house and the heat generated by the fuel cell is also shared by each household. According to [30], a cogeneration system based on fuel cell is proposed. The system is installed on a dwelling container. Roughly the system efficiency reaches up to 83%. The actual efficiency

of a PEMFC is not greater than 37%. The remaining percentage of hydrogen goes waste in the form of heat. Some of the advantages of cogeneration using Fuel cells are given in [23] are Better utilization of waste heat results in increase in electric efficiency. Cogeneration also decreases the overall expenditure on the power and heat requirements. It is environment friendly as it minimizes the use of CFCs and HCFCs.

2.6. Hydrogen production and Storage

Hydrogen is present in over 75 percent of the known matter. Although it does not exist in its natural form i.e. pure hydrogen but it is present in the form of compounds most importantly water. Due to shortage of fossil fuel more people are going to face energy shortages in the coming decades. Hydrogen as a fuel gives an alternative and clean source of energy. However hydrogen as a fuel requires a lot of research work which is required to overcome technological barrier to make hydrogen as available replacement for fossil fuels [31]. Hydrogen as a fuel for the fuel cells gives an excellent alternative because they have high efficiency as compared to internal combustion engines [19]. PEMFC using hydrogen as the fuel is the most clean and environment friendly sources of energy [32]. Large scale production of hydrogen using clean, reliable and cheap process is very important for commercialization of hydrogen [33]. As explained in [32, 33] hydrogen can be produced using various processes which are briefly given below:

(a) Natural Gas Reforming:

In this process high temperature steam is used to obtain hydrogen from natural gas which has methane as its chief component. This process is also called steam methane reforming. In another method methane is burned in air to obtain synthesis gas which is then reacted with additional steam to produce hydrogen. This method is called partial oxidation.

(b) Gasification:

In this process heat is applied to coal or biomass under pressure and in the presence of oxygen. After a series of chemical reaction a synthesis gas is produced, this is then reacted with steam to produce a high concentrated hydrogen steam that can be separated.

(c) Renewable liquid Reforming:

In this process Biomass is converted to make ethanol which is then reacted with high temperature stem to produce hydrogen. Ethanol or bio-oil can be easily transported and are also known as renewable liquid fuels.

(d) Nuclear High-Temperature Electrolysis:

In this process heat from the nuclear reactor is utilized to raise the water temperature. By increasing the water temperature less amount of electricity is required to split hydrogen and oxygen from water. Thus total energy required to produce hydrogen is reduced.

(e) High-Temperature thermo chemical water splitting:

This method uses high temperatures generated by solar concentrators to facilitate the chemical reactions involved in splitting of water for hydrogen production.

(f) Biological:

By this process hydrogen is produced using natural processes in certain microbes such as green algae, cyanobacteria which produce hydrogen by splitting water as a byproduct in their natural metabolic process in the presence of sunlight.

(g) Photo-Electrochemical:

In this process a special class of semiconductor is used to separate water molecules to hydrogen and oxygen by absorbing sunlight.

(h) Renewable Electrolysis:

In this process electricity is used to split water molecules. The electricity required is generated renewable energy resources such as wind, solar, hydro, geothermal, nuclear etc. thus it minimizes the green house gases emissions.

Table 2.3
Some major developers of fuel cells [2]:

Company	Fuel Cell Type	Power	Application
Hitachi-global	PEMFC, DMFC	100-300 W	Medium sized stationary
ITM Power	PEMFC	Up to 1kW	Medium sized stationary
Clear Edge power	AFC	5 kW	Stationary
Eneos celltech	PEMFC / SOFC	750 W	Stationary
Matsushita	PEMFC	1 kW	Stationary
Plug Power	PEMFC	5 kW	Stationary
Nedstack	PEMFC	2-100 kW	Medium sized stationary

2.7. Fuel Cell based microgrid

Fuel cell based microgrid is emerging as new alternative to photovoltaic and wind based microgrid because of its easier installation and higher efficiency. However Fuel cells have

following drawbacks as mentioned in [12] which show that Fuel cells have slow response in the event of change in load, unable to store energy and they have Fluctuating output voltage with change in load. These shortcomings can be overcome by the use of dc converters, battery or super capacitors.

According to [34] the photovoltaic (PV) sources have many advantages like desired level of installation capability. However PV generation cannot be used independently because of the uncertainty in their production performance. So the PV generation model must be used with some other generation models like Fuel Cells to provide more reliable and efficient service. A hybrid fuel cell is proposed in [35] consists of a fuel cell connected with unidirectional dc-dc converter, a battery connected with bi directional dc-dc converter and an inverter. During the start of the system only battery provide power to the load as fuel cell has a late response. So for providing a reliable supply to load initially battery is run. During step up or down of load, battery provides or absorb the unbalanced energy.

In [36], a hybrid system is proposed which consist of a PV array and a proton exchange membrane fuel cell (PEMFC). The PV array is used such that it delivers maximum power to load by the use of maximum power point tracking technique (MPPT). But when there is variation in the sun radiation, temperature, the PV array becomes uncontrollable source. So in this case the PEMFC is used to make the system more reliable and controllable. A DC microgrid proposed in [37] consisting of a fuel cell, super capacitor and battery as DGs and the DC bus connects output of the Solid State Transformer (SST). SST operates bi-directionally and acts as a interface between fuel cell, battery and the load. The battery acts as an energy buffer and gives supply to load when its State of charge (SOC) is in operating range.

[38] Explains a multi DER system consisting of Diesel generator, fuel cell, combined cycle gas turbine based system, aqua electrolyzer is considered as controllable source of microgrid. These controllable sources are regulated on the basis of frequency deviation from the preselected value because in case of a mismatch in the power requirement of load and power generation then the gap is met by inertial energy and hence the system frequency changes. Also in case when generated power bypasses the required value then that additional power is stored in aqua electrolyzer to produce hydrogen for the fuel cell. In [39] an islanded distribution network consisting (IDN) of PV, fuel cells, batteries as DGs is proposed. IDN

uses energy management system (EMS) and supervisory control and data acquisition system (SCADA) to improve reliability of microgrids in case of blackouts.

2.8. Inference

Fuel cell is one of those renewable distribution energy based technology that are capable of lowering the pollution by effectively replacing the fossil fuel based energy generating system. In this report a literature review of different types of fuel cells were explained. Some technological barriers like slow response to changing load conditions which are hampering the commercialization of fuel cell are also reviewed. The different types of proton exchange membranes that have evolved over the years are described. It is realized that a lot of research has been done in the different type of fuel cells and each fuel cell with certain capabilities can be used in different applications. For example, PEMFC which operates at comparatively lower temperature, have a lower response time should be used for automotive applications. Out of all the fuel cells SOFC, operate at higher temperature so the additional heat can be utilized for the cogeneration applications, making SOFC a prime candidate for the CHP (combined heat and power) applications. This provides additional energy from the fuel cells in the form of heat and also increases the fuel cell efficiency. Also in case of SOFC, the fuel and the oxidants that are injected into the fuel cell needs to be preheated, so the heat generated by SOFC could be used for preheating in the fuel processor. The electrical energy used by the fuel cell components like fuel processor, water and thermal management systems needs to be optimized so as to improve fuel cell efficiency.

Through this literature survey it becomes evident that the recent advances in the fuel cell technology have made it possible to be used in microgrid applications. Fuel cells can deliver uninterruptible power supply as long as fuel, such as hydrogen and oxygen are supplied to it. This is an advantage over other DGs that are used in microgrid as they suffer from natural uncertainties and changing weather conditions. Moreover, this survey also shows that the slow response characteristic of fuel cells can be eradicated when they are used with batteries or super capacitors. Lot of research activities have been initiated worldwide focusing on deployment of fuel cell technology as a component of microgrid system which has been observed in this report and written as a comprehensive literature survey on fuel cell deployment.

Chapter 3

Modelling and Simulation of a Fuel Cell System Supplying Power to a Separately excited DC Motor

3.1 Introduction

During the course of literature survey, it was realized that the effect of dynamic load through application of rotational machines supplied by the microgrid system are to be investigated. It is also revealed in literature survey that most of the research work in this work is focused on the application of fuel cell supplying dc motors installed in Electric vehicles. In our case such as for microgrid applications, the study of rotational machines and their effect on microgrid sources are required to be explored and also it is found in literature survey that few numbers of researches have been done in this field.

Now for the rotational machines broadly there are two options available such as dc machines and ac machines which are to be supplied by dc and ac sources respectively. In this dissertation work, the author has selected to study the effect of variation of load torque of a separately excited dc motor which is supplied by the Fuel Cell system. Since this work deals with dc microgrid system that is why study is focused on the effect of load variation in case of dc motor. It will be relevant to mention that same kind of study could be possible if ac motors such as three phase induction motors is used instead of dc motor application. But in that case the sample system which is a fuel cell based microgrid system is required to be modified by connecting a three phase inverter to supply the ac motor by additional cost factor to the existing system.

Due to these reasons, the proposed microgrid model is tested while supplying a separately excited dc motor as described in the present chapter. The output characteristics of PEM Fuel Cell and response characteristics of dc motor are analyzed. Whole system is investigated in Matlab/Simulink and the results obtained from simulation are validated with mathematical results. In this chapter effect of fuel flow rate on stack efficiency and stack voltage was also investigated to analyze the impact changing input variations within the PEM fuel cell.

3.2 Modeling and Simulation of Fuel Cell System

A 6kW, 45V Proton Exchange Membrane Fuel cell is used for simulation using Matlab/simulink. Hydrogen is fed as a fuel and air as oxidant to fuel cell. A simulation model

to study the response of fuel cell to a dc motor as load is studied. A stack of 42 cells with a nominal efficiency of 46% is chosen. As per the options available in FC block in Simulink, the fuel cell block can be either a simplified model or detailed model. Here detailed model is chosen to include the number of fuel cell used. In the detailed model parameters like fuel flow rate, air flow rate system temperature, fuel composition, oxidant composition, fuel supply pressure and air supply pressure can be varied.

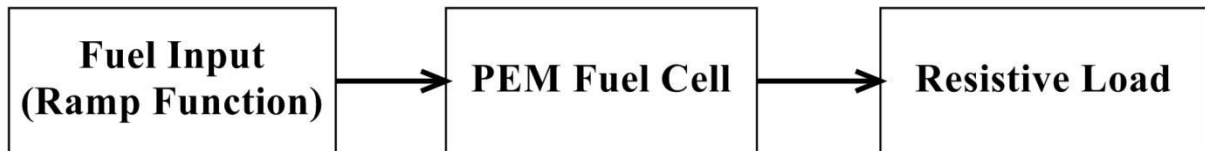


Figure 3.1 Fuel cell system supplying power to resistive load

Here fuel flow rate is varied as a function of output current of the fuel cell. The feedback loop of the fuel cell output current controlling the fuel flow rate is mentioned in the detailed model given in Matlab/simulink library. Initially the effect of changing fuel input and system temperature to the output voltage and current is analyzed using Matlab/Simulink. Fuel flow rate is in liter per minute, system temperature is in Kelvin and the effect of temperature and humidity of the membrane on the internal resistance is not considered. The fuel flow rate is simulated as ramp input to the PEM fuel cell and system temperature is chosen constant at this stage of simulation as shown in Fig. 3.2 the slope of the ramp function is unity and the output results are shown below:

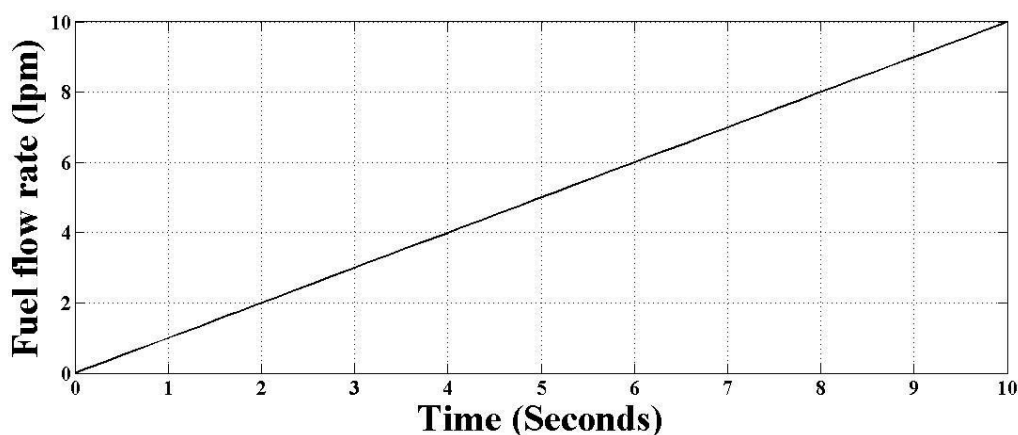


Figure 3.2 Fuel flow rate (Ramp input)

It is observed from the Fig. 3.3 and 3.4 that as fuel flow rate is increased the output voltage and current of the fuel cell also increases proportionately. After 2 seconds of the simulation the voltage and current of the fuel cell become constant even when the fuel flow rate is

increased. The variations of FC voltage is shown in Fig. 3.3 and variation in FC current is shown in Fig 3.4

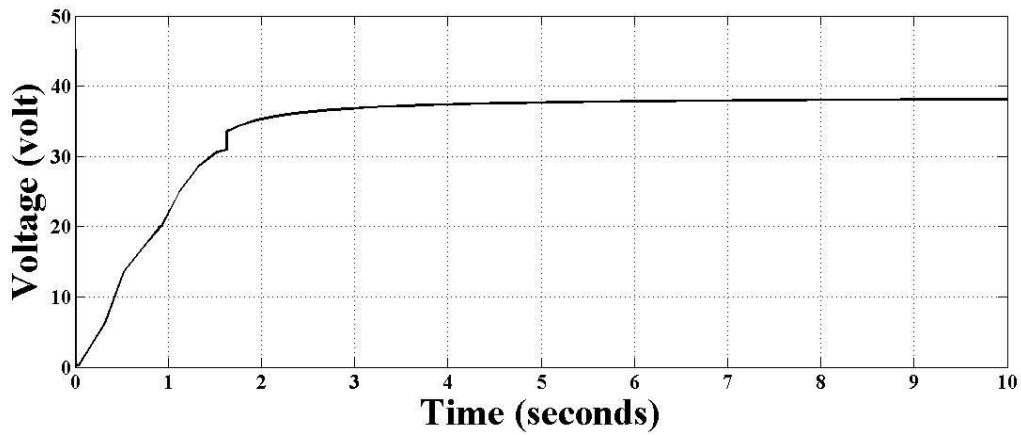


Figure 3.3 Fuel cell Voltage

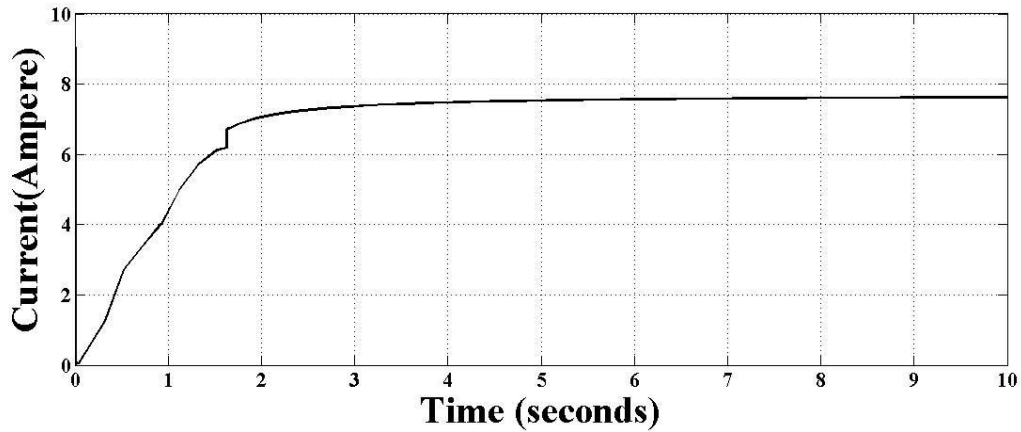


Figure 3.4 Fuel cell Current

3.3. Study on variation of load torque of a separately excited DC motor.

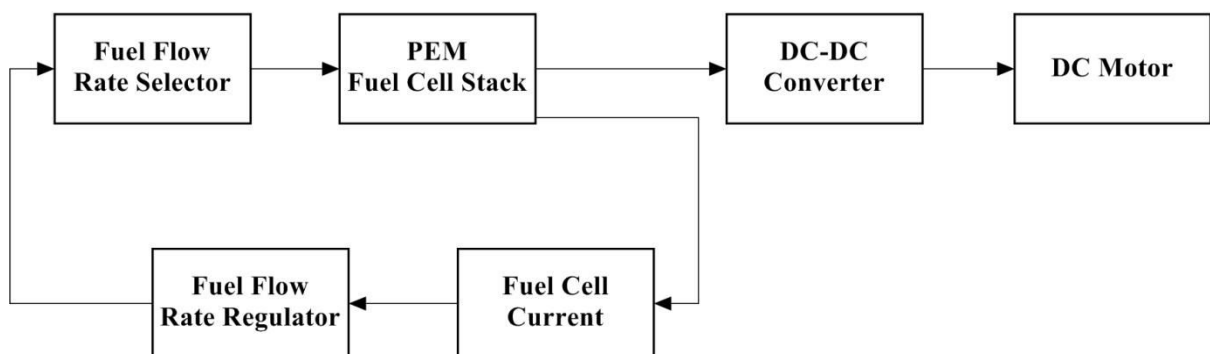


Figure 3.5 Fuel cell supplying Power to DC Motor

3.3.1. Model Description

The PEM Fuel cell stack consisting of 65 cells supplies DC power to motor through DC-DC boost converter. The Fuel cell considered is a 6 kW, 45 Volt and motor is a 1.25 hp, 610 rpm, separately excited DC motor. The fuel flow rate in the PEM Fuel Cell stack is regulated by fuel flow rate regulator according to the variations in the Fuel cell current. The detailed modelling of DC-DC converter, DC motor, Fuel flow rate regulator is given in sub-sections 3.3.2, 3.3.3 and 3.3.4.

3.3.2. Modelling of DC-DC Converter

The dc-dc boost converter step up the dc voltage from the output of fuel cell stack. Also the unregulated supply from the fuel cell stack is transformed into a regulated supply voltage which can be directly fed to load. The simulink model of the dc-dc converter is shown below fig. 3.6. The diagram consists of an IGBT based chopper of which the duty cycle is controlled by PI based feed-back loop as shown in the figure:

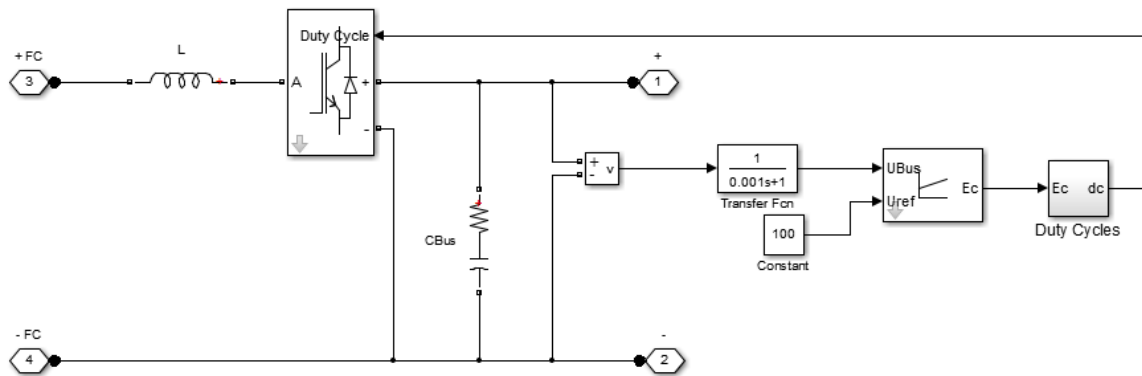


Figure 3.6 Simulink model of DC-DC Boost Converter

The steady state analysis of dc boost converter is presented below [40]: For the steady state analysis the inductor voltage V_L is assumed to be zero

$$V_L = D (V_{in}) - (1-D) (V_{in} - V_O) = 0 \quad \dots (3.1)$$

Ratio of output to input voltage, gain ratio is given by:

$$M = \frac{V_O}{V_{in}} = \frac{D}{1-D} \quad \dots (3.2)$$

The inductor current is given by:

$$V_{in} \cdot I_L = V_O \cdot I_O \quad \dots (3.3)$$

$$I_L = \frac{v_o}{v_{in}} \cdot I_o \quad \dots (3.4)$$

From (3.3) and (3.4), the inductor current is expressed as:

$$I_L = M \cdot I_o \quad \dots (3.5)$$

3.3.3. Modelling of Separately excited DC Motor

The armature windings and field windings of separately excited DC motor are given DC voltage input from the fuel cell as 100 volt constant dc source. The motor is 1.25 hp, 100 volt, 610 RPM separately excited DC motor with field and armature resistance of 100 ohm and 0.4 ohm respectively. The field inductance of DC motor is 1.5 H. The Simulink model of separately excited DC motor showing the armature and field windings is presented in Fig. 3.7. From the measurement port motor speed, torque and armature current can be observed. The load torque is varied as a function of speed as shown in equation 3.8.

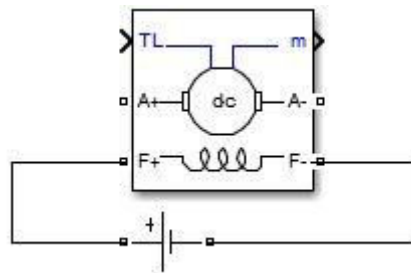


Figure 3.7 Simulink model of separately excited DC motor

The electric motors are the main components of any manufacturing industry and electric hybrid vehicle. The relationship between torque and speed is a very important aspect of dc motor application [41]. The voltage constant of a separately excited dc motor is given by:

$$K_E = L_{af} \cdot I_f \quad \dots (3.6)$$

Where, L_{af} is field armature mutual inductance and I_f is the field current. The electrochemical torque developed by dc motor is given by:

$$T_e = K_T \cdot I_a \quad \dots (3.7)$$

Where, K_T is torque constant and I_a is the armature current. For the motor to operate satisfactorily, the load torque and the electrical torque must be greater than zero. For the mechanical input, load torque is provided as proportional to motor speed in radians / sec.

$$T_L = BLW \quad \dots (3.8)$$

The mechanical part implements equation, $J \frac{dw}{dt} = T_e - T_L - B_m w - T_f$... (3.9)

Where, J = inertia, B_m = viscous friction coefficient, T_f = coulomb friction torque. The speed of the dc motor is given by:

$$N = \frac{V - I_a R_a}{\phi Z} \times \frac{60A}{P} \text{ RPM} \quad \dots (3.10)$$

R_a = Armature resistance, A = number of parallel paths, Z = number of armature conductors, ϕ = flux / pole, P = number of poles.

The back emf of motor is given by: $E_b = V - I_a R_a$... (3.11)

$$\text{Now, } I_a = \frac{V - E_b}{R_a} \text{ Ampere} \quad \dots (3.12)$$

The back emf produced by dc motor helps to counter large armature current. The back emf is proportional to speed. Therefore at the start of motor the back emf is zero. So to protect motor from the large inrush current, motor starters are provided. Figure 3.8 presents a three point starter. To limit the high inrush current initially a resistance of 3.66 ohm was used then as the motor speed raises the back emf also increases and thus armature current decreases and so is the value of starter resistance. Hence for the protection of dc motor against the high starting current, it is necessary to connect a high resistance at the instant of starting in series with the armature.

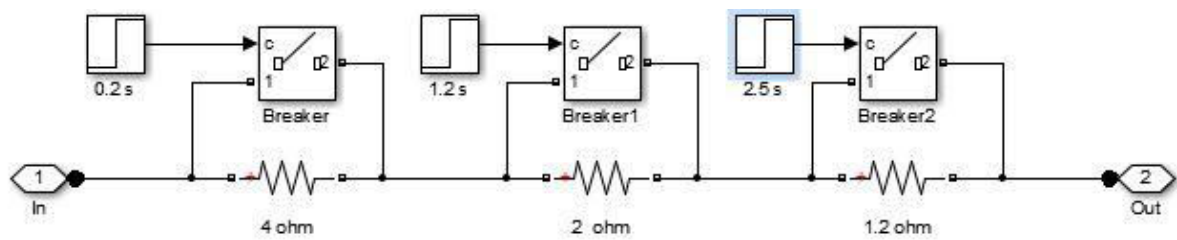


Figure 3.8 Simulink model of three point Starter

To study the effect of a dc load, a 1.25 hp, 100V, 610 rpm motor is connected across a 6 kW, 45V PEM fuel cell. In this system the nominal voltage of fuel cell is 45 volts and the nominal operating current is 133.3 A. Stack of 65 cells is used with a stack efficiency of 55%.

3.3.4. Mechanism of fuel flow rate regulator

The fuel flow rate regulator consists of a function block with following parameters:

$$\text{Flow rate} = 60000 * R * (273 + T) * N_c * u(1)/2F(101325 * P_f) * (u_{fH_2}/100) * (x/100) \quad \dots (3.13)$$

where $R = 8.3145 \text{ J/ (mol K)}$; $T = \text{operating temperature} = 65 \text{ degree Celsius}$; $N_c = \text{number of cells in series} = 65$; $u(1) = \text{current}$; $F = 96485 \text{ A s/mole}$; $P_f = \text{fuel pressure} (1.5 \text{ bar})$; $u_{H_2} = \text{nominal hydrogen utilization}(99.56\%)$; $x = \text{Hydrogen composition} (99.95\%)$ [42].

3.3.5. Simulation of FC supplying power to separately excited DC Motor

The model shown in fig.3.5 is run for 15 seconds. During first 10 seconds the flow rate is varied according to variation in the fuel cell current. After 10 seconds the fuel flow regulator is bypassed to study the effect on stack voltage and stack efficiency. The flow rate is varied according to variation in fuel cell current as shown in the equation 3.13. All the parameters except fuel cell current are kept constant. The fuel flow regulator gives simulink signal to flow rate selector. The flow rate selector implements a logic signal such that till $t = 10 \text{ sec.}$ the flow rate is varied by the fuel flow regulator. After 10 sec., fuel flow regulator is bypassed using a switch as shown in fig 3.9 and fuel is supplied by a ramp signal with an upper limit of 50 lpm using a saturation signal. It is observed in the Simulink results as shown in fig. 3.10, 3.11 and 3.12 that after 10 sec. the stack/Nernst voltage rises and stacks current decreases and therefore efficiency drops.

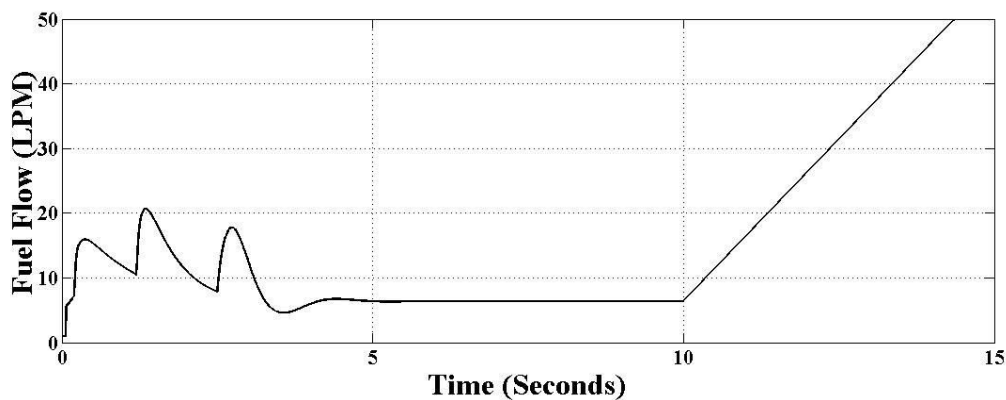


Figure 3.9 Fuel flow rate

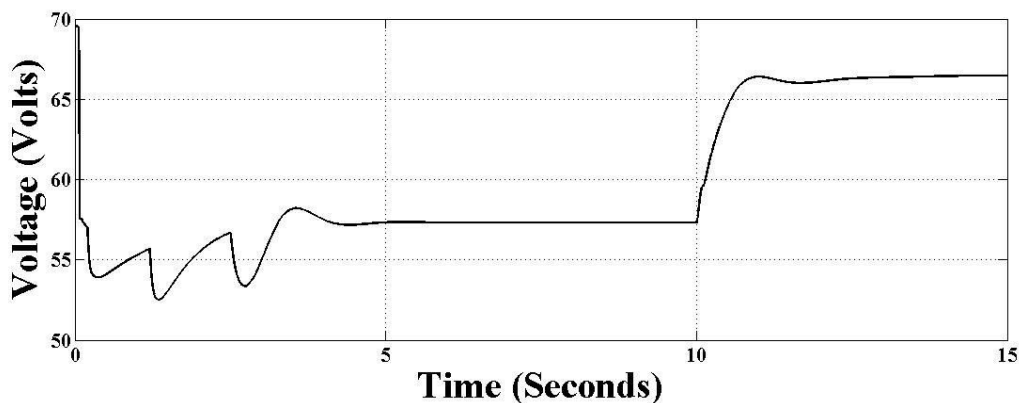


Figure 3.10 Fuel cell Voltage

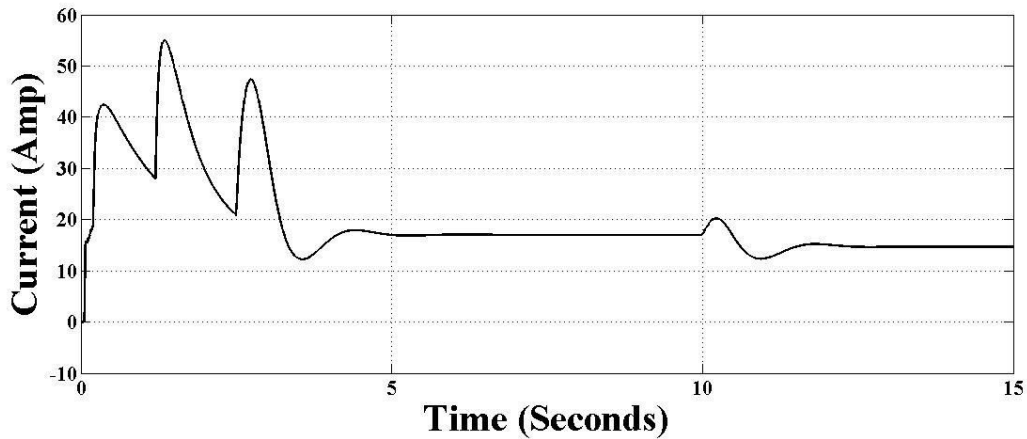


Figure 3.11 Fuel cell Current

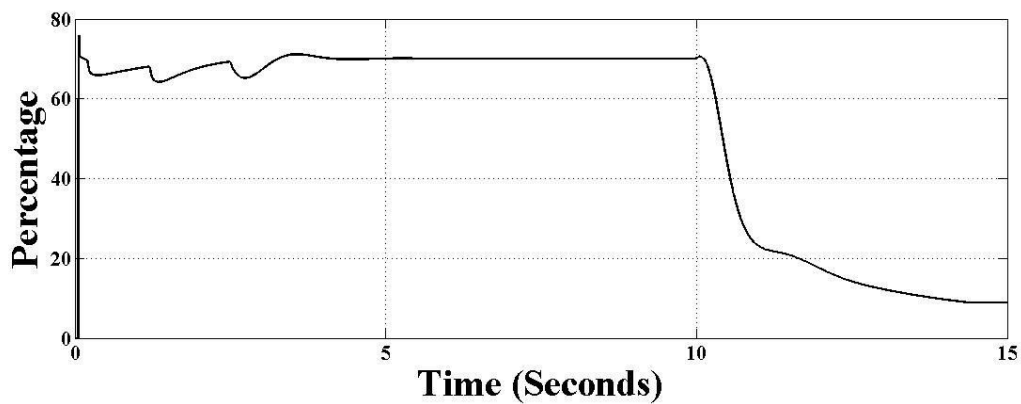


Figure 3.12 Fuel cell Efficiency

The motor is connected across the fuel cell through a dc-dc boost converter. The fuel cell voltage is stepped up from 45 volts to 100 volts using dc-dc converter. The dc-dc boost converter also regulates the output voltage of PEM fuel cell. The field winding of the dc motor is excited externally through a 100 volt battery. The motor has the armature resistance of 0.4 ohms and inductance of 0.008 H. The field resistance and inductance of motor is 100 ohms and 50 H respectively. The simulation model was run for 15 seconds.

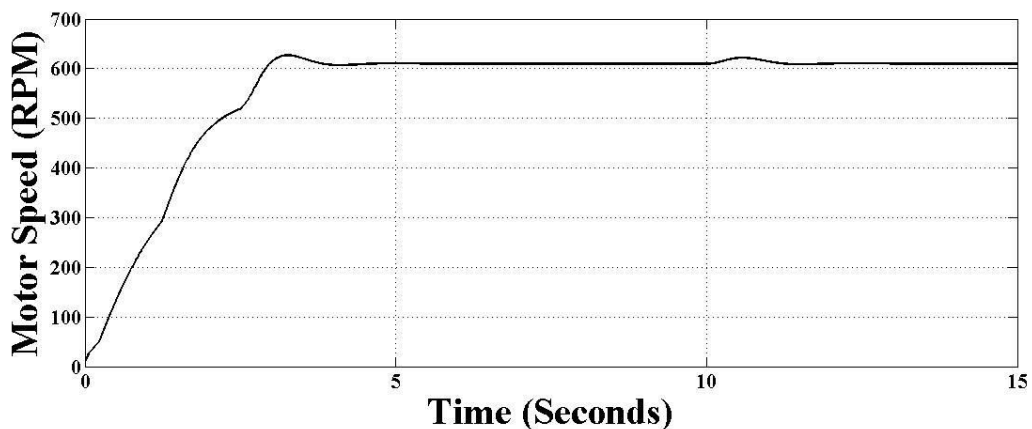


Figure 3.13 Speed of DC Motor connected to Fuel cell

It is observed that the electrical torque generated and the corresponding power also reaches steady state value after 4 seconds. The resulting wave forms depicting variations in the motor parameters such as electric torque, power and armature current are given in fig. 3.13 to 3.16 show initial transients due to variation of resistance in three point starter used to limit the starting current of armature circuit.

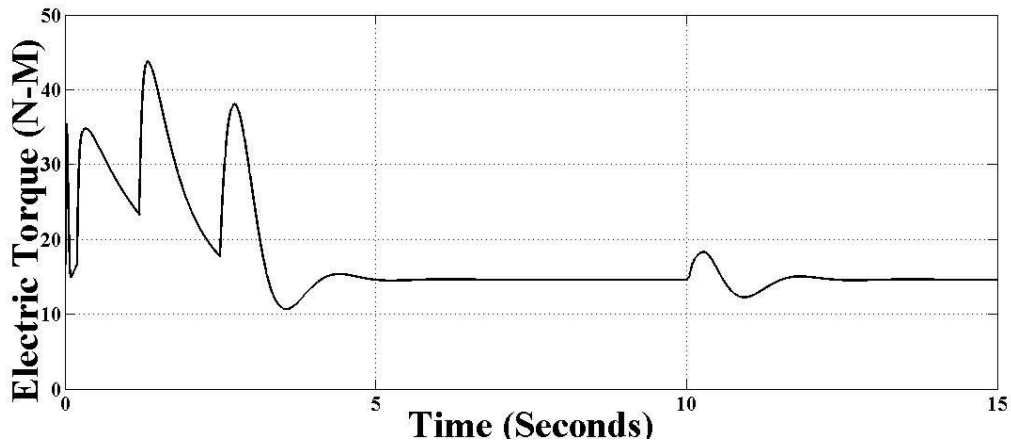


Figure 3.14 Motor torque when connected to Fuel cell

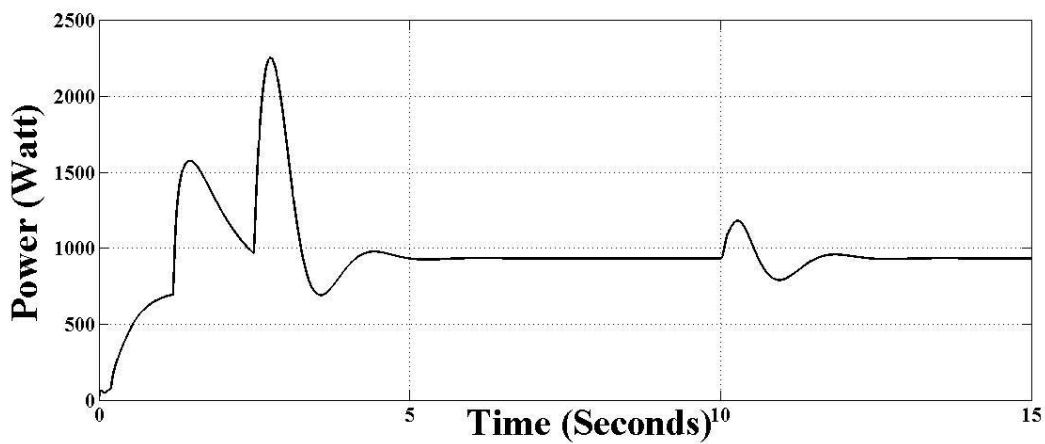


Figure 3.15 Motor Power when connected to Fuel cell

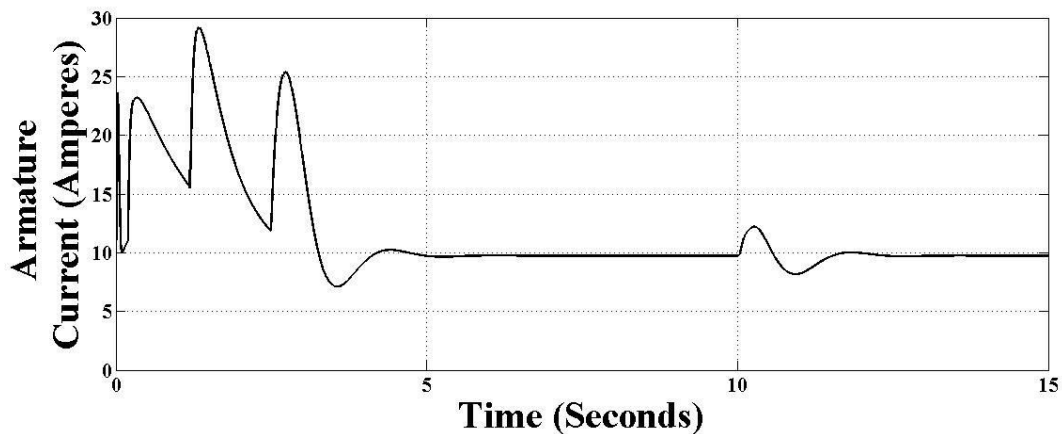


Figure 3.16 Motor Armature Current when connected to Fuel cell

After initial transients, steady state value of various parameters are observed and given below:

$$\text{Armature current, } I_a = 9.735 \text{ A} \quad \dots (3.14)$$

$$\text{Motor Power, } P_e = 935 \text{ W} \quad \dots (3.15)$$

$$\text{Motor speed, } N = 610 \text{ RPM} \quad \dots (3.16)$$

$$\text{Electric Torque, } T_e = 14.62 \text{ N-m} \quad \dots (3.17)$$

In the following sections the same parameters are calculated based on the motor equation as shown below:

$$\text{Now for the DC Motor field inductance is given by, } L_{af} = 1.5 \text{ H} \quad \dots (3.18)$$

$$\text{Field Resistance, } R_f = 100 \text{ ohm} \quad \dots (3.19)$$

$$\text{Terminal voltage, } V = 100 \text{ volts} \quad \dots (3.20)$$

$$I_f = \frac{V}{R_f} = 1 \text{ A} \quad \dots (3.21)$$

$$\text{Now, back emf, } E_b = V - I_a R_a = 96.06 \text{ V} \quad \dots (3.22)$$

$$\text{Electric Power, } P_e = E_b * I_a = 935.591 \text{ W} \quad \dots (3.23)$$

$$\text{Also, } E_b = W * L_{af} * I_f \quad \dots (3.24)$$

$$\text{Therefore motor speed, } W = E_b / (L_{af} * I_f) \quad \dots (3.25)$$

$$W = \frac{96.106}{1.5 * 1} = 64.07 \text{ radians per second.} \quad \dots (3.26)$$

$$\text{Nominal Torque, } T_e = \frac{P_e}{W} = 14.6 \text{ N-M.} \quad \dots (3.27)$$

3.3.6. Inference

It is observed that values of motor parameters obtained from the mathematical equations 3.21 to 3.27 of the separately excited DC motor justify the results obtained from simulation. The motor runs satisfactorily with the fuel cell supplying regulated power through DC-DC converter. It is also observed that the efficiency of the fuel cell is affected by the variation in the fuel flow rate. When the fuel flow rate is varied according to equation 3.13, the fuel cell efficiency was 65-70% as shown in Figure 3.12 and when fuel flow rate was abruptly increased the efficiency decreases to 15%.

Chapter 4

Performance Analysis of Proposed Fuel cell based DC Microgrid

4.1 Introduction

The conventional electrical system that we are used to consists of AC supply being generated, transmitted and distributed. But as the development of renewable sources like solar, wind, fuel cell grows, the dc microgrids become efficient, reliable and cost effective option. A fuel cell based DC microgrid is a viable option in the areas having no grid connectivity. Fuel cells are good source of power generation due to their ability to deliver round the clock power. The emission free and silent operation of fuel cell makes them better in comparison with the internal combustion engines.

Fuel cells have efficiency range from 40-60 percent and can be upto 80 percent with the cogeneration. Like AC microgrid, the DC microgrid operates in grid connected as well as grid independent / islanded mode. The modern electric loads such as Laptops, LED, plug in hybrid vehicles operate in DC mode and more over AC loads like induction motor when driven with the help of variable speed drive require DC supply. The DC microgrids have proven to be superior in terms of efficiency, low cost due to absence of conversion system like inverter [43]. In grid connected mode, the power is supplied by the main grid. This mode can be operated in case of non availability of fuel cell due to any fault or during the shortage of fuel supply. Due to intermittent nature of distributed energy resources and for more reliable service to the consumer, especially critical load like hospitals etc., an energy storage unit is required. Also during the transition time, the energy storage unit can be made to supply the power to load. The energy storage unit may be a battery or super capacitor.

As soon as the battery / supercapacitor discharges below the nominal supply needs of the load, the grid can be connected till the fuel cell is restored. Considering the economic aspect batteries are more popular and also their maintenance is quite easy in comparison with super capacitors. The DC grid must meet the requirement of constant voltage supply for the satisfactory operation of the load. In grid independent mode the load is not connected to the main grid and it depends on fuel cell, battery for the power requirements.

4.2 Simulation of Grid connected and Islanded mode operation of the proposed Fuel cell based Microgrid Supplying Power to DC motor

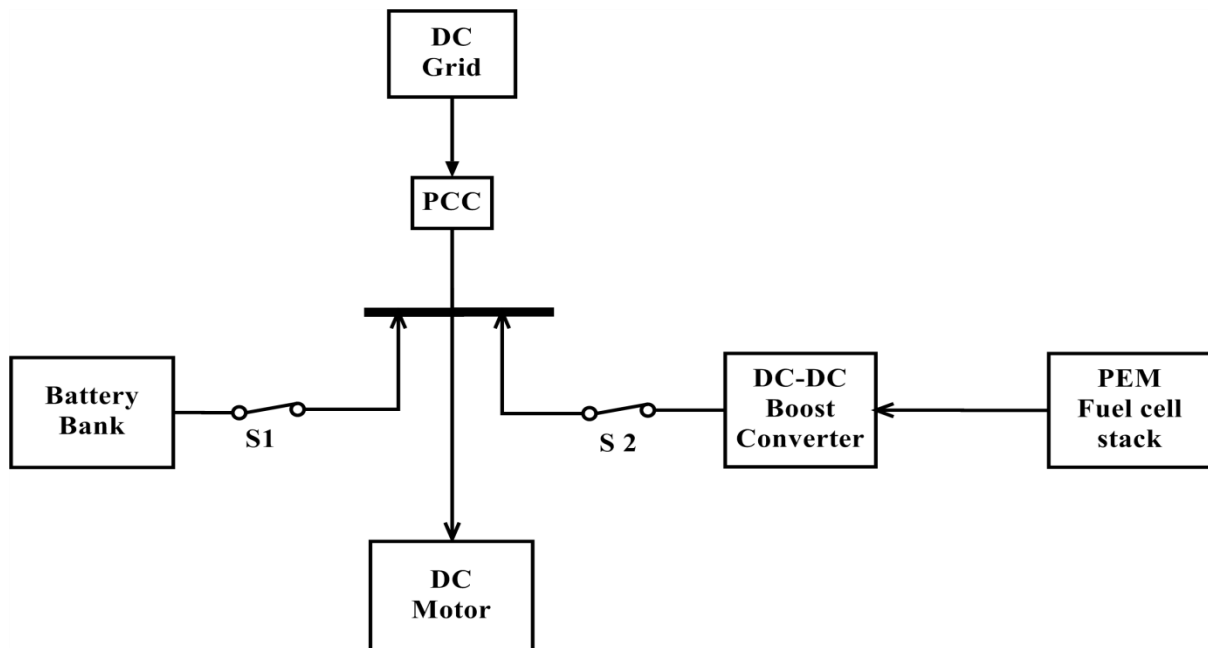


Figure 4.1 Schematic Diagram of Fuel cell based Microgrid supplying Power to DC Motor

4.2.1. Model Description

The model consist of a 100 volt DC grid interfacing with the battery bank and fuel cell stack at a point of common coupling (PCC). The specifications of battery connected is a 100 volt, 5 Ah lead acid battery. It acts as an auxillary power source, when Fuel Cell or grid is unable to supply power to load. The battery can also be used along with fuel cell, thereby sharing power with the load and reducing the fuel consumption. The output parameters of the fuel cell, dc motor and the boost converter are same as explained in Chapter 3. The DC grid, Fuel cell stack and the battery bank can be connected or disconnected by operating PCC, Switch (S1) and Switch (S2) respectively. The operation of these switches will depend on the availability of the generating source and the system requirement.

4.2.2 Simulation and Results

The simulation model is run for 100 seconds. From 0-50 seconds both fuel cell and battery supply power to load. Initially the battery charges from the fuel cell. As soon as battery is capable enough to share power with the fuel cell, it starts supplying power to motor along with the fuel cell. After 50 seconds the Fuel cell is disconnected from the load. From 50-70 sec. only battery supplies power to the motor. During this time interval, the battery

discharges. From 70-100 sec. battery is disconnected and load is connected only with the DC grid. The detailed values and waveforms obtained after running the model are given below:

4.2.3. Waveforms

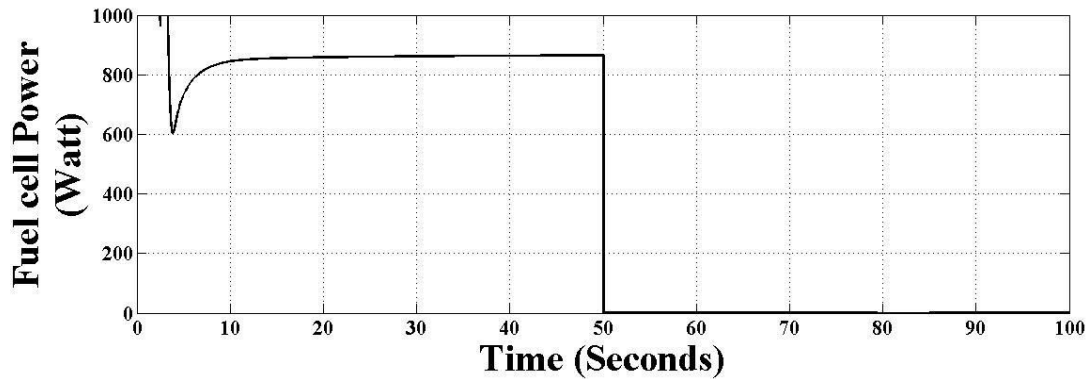


Figure 4.2 Power Supplied by Fuel Cell to the DC Motor

The Fuel Cell and the battery bank supplying power to load are shown in fig. 4.2 and 4.3. From 50-70 seconds, Fuel Cell is disconnected and the power supplied by battery to load is shown in fig. 4.3

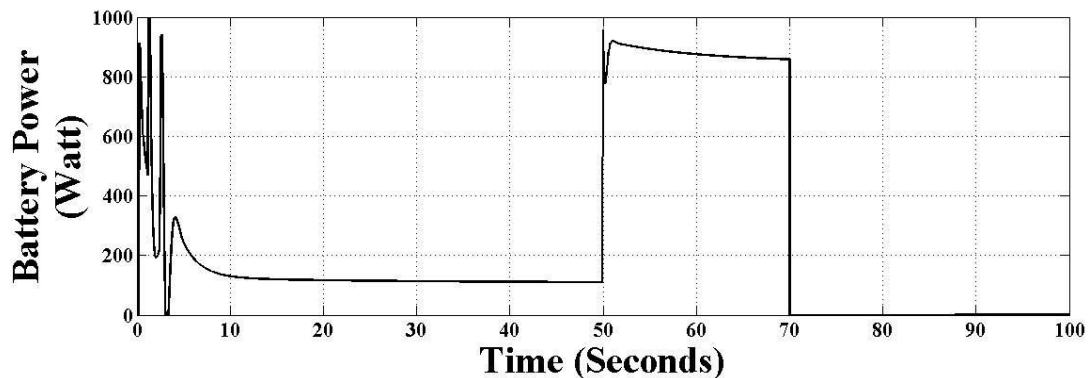


Figure 4.3 Power Supplied by Battery Bank to the DC Motor

The DC grid remains disconnected until the FC based Microgrid and the battery bank are supplying power to the separately excited DC motor. As soon as the Fuel Cell and the battery bank are disconnected the grid start supplying power to the load as shown in fig 4.4. The power supplied by FC based microgrid and the DC grid to separately excited DC motor can be varied according to the availability of hydrogen as fuel for operating the Fuel Cell. Also the state of charge of the battery bank is important factor to determine the grid connected or islanded mode of operation of the FC based microgrid at various time intervals. The operation for the FC based microgrid supplying power to separately excited DC motor in this case is shown in fig. 4.5.

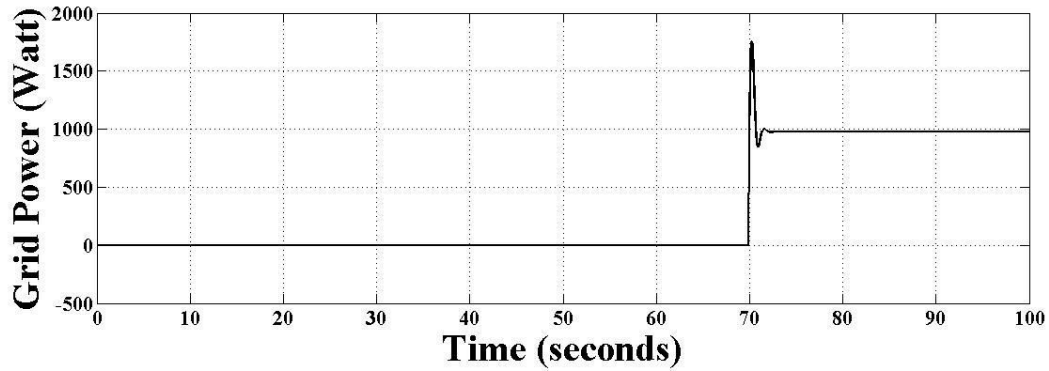


Figure 4.4 Power Supplied by Grid to the DC Motor

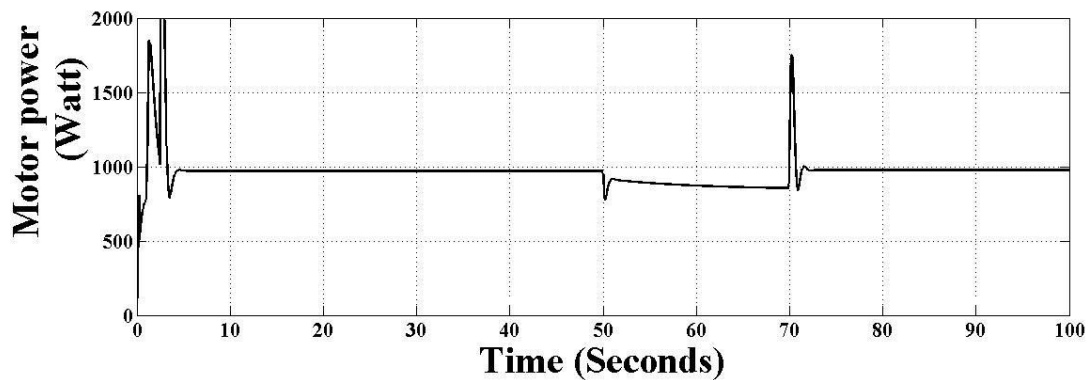


Figure 4.5 Motor Output Power

Table 4.1 and 4.2 show the current and power sharing between fuel cell, battery and DC grid while delivering power to separately excited DC motor.

Table 4.1
Current distributions of various Power sources and load

S.No.	Time Duration (sec.)	Fuel cell Current, I_{fc} (Ampere)	Battery Current, I_b (Ampere)	Grid Current, I_g (Ampere)	Motor Current, I_a (Ampere)
1	0-10	8.47	1.3	0	9.77
2	10-50	8.647	1.08	0	9.73
3	50-70	0	9.131	0	9.12
4	70-100	0	0	9.76	9.76

Table 4.2
Power distributions of various Power sources and load

S.No.	Time Duration (sec.)	Fuel cell Power, P_{fc} (Watt)	Battery Power, (P_b) (Watt)	Grid Power, P_g (Watt)	Motor Power, P_m (Watt)
1	0-10	844.6	130.1	0	970.9
2	10-50	864	110	0	970.9
3	50-70	0	858	0	854.6
4	70-100	0	0	977.6	976.5

4.3 Microgrid Supplying Power to Critical and Non Critical Loads

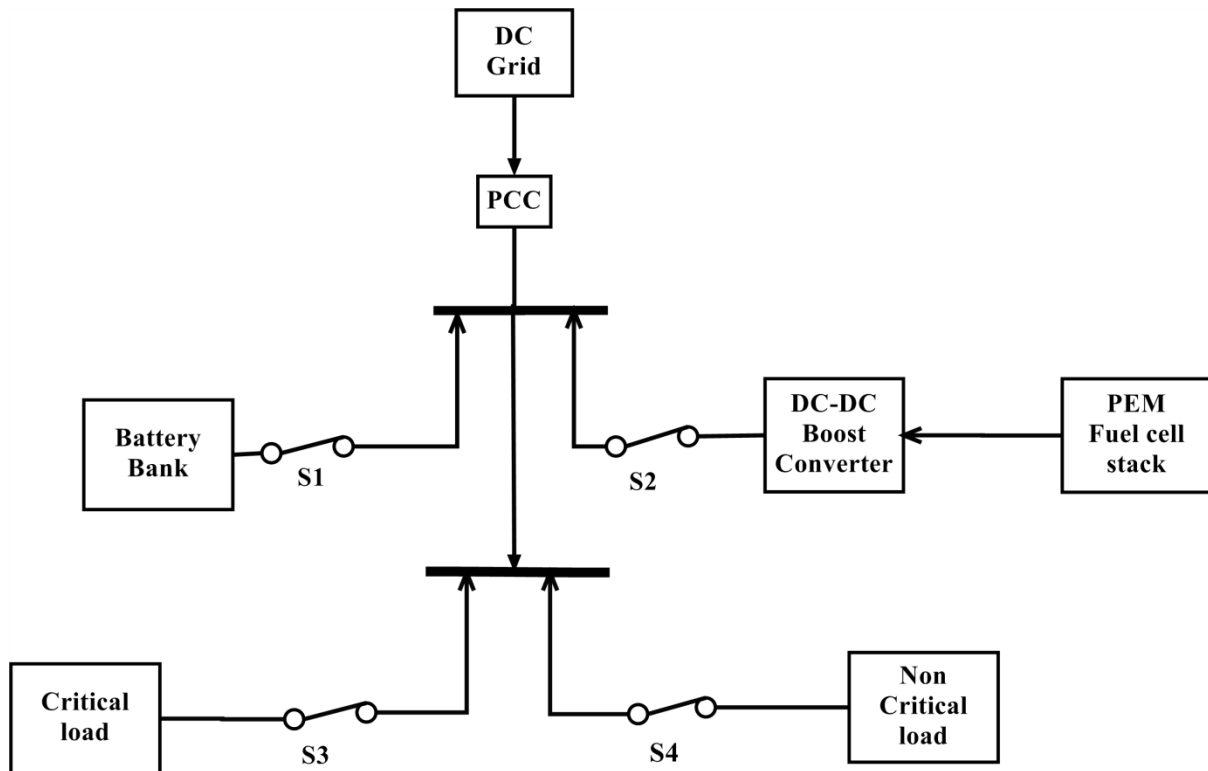


Figure 4.6 Schematic Diagram of Fuel cell based Microgrid Supplying Power to Critical and Non-Critical Loads

4.3.1. Model Description

The above microgrid model supplies load to critical and non critical loads. Critical loads are defined as loads which should not be curtailed, these include hospitals, railway stations etc. Non critical loads are residential or those loads which can be shed in the event of shortage of power. In the above model non critical loads are disconnected when power is available only from the auxillary source which in this case is the battery. Critical load is not disconnected in any case. The load power across critical and non critical load is 3 kW and 7 kW. Thus total power to be supplied by Fuel Cell based microgrid is 10 kW. The DC grid, Fuel Cell, battery bank, dc-dc converter which are used to supply power to critical and non-critical loads are already explained in Chapter 3. These renewable energy resouces can be connected or disconnected from the load depending upon the fuel availability and charge level of energy storage system which in this case is a battery bank.

4.3.2 Simulation of a FC based Microgrid supplying Power to critical and non critical load.

The simulation model is run for 100 sec. For 0-50 sec both battery bank and fuel cell are

supplying power to critical and non critical load and there is current and power sharing between battery bank and the Fuel Cell. From 50-70 seconds the fuel cell and non critical load is disconnected and power to the critical load is supplied only by the battery bank. From 70-100 sec. the power is supplied by the DC grid to both critical and non critical load. The fuel cell and battery bank remain disconnected during this time interval.

4.3.3. Waveforms

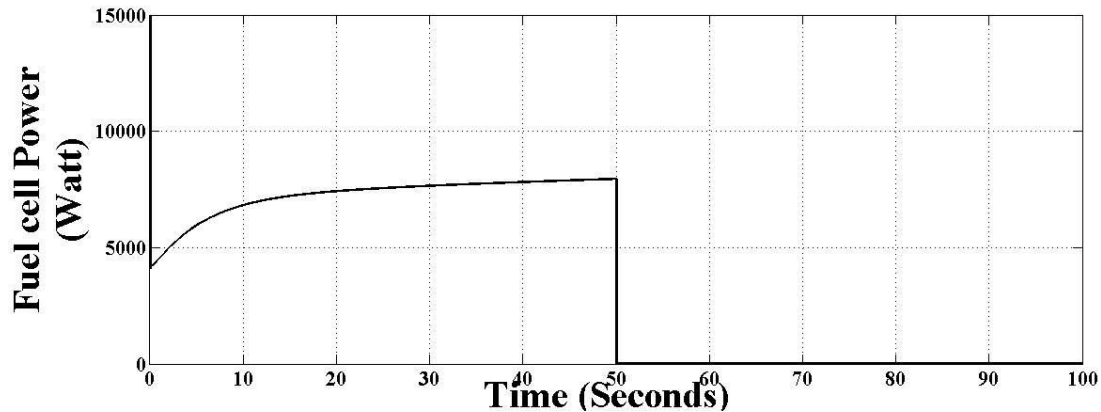


Figure 4.7 Power Supplied by Fuel cell to the Load

The Fuel Cell and the battery bank supplying power to Critical and Non-Critical load is shown in fig. 4.6 and 4.7. From 50-70 sec. the power is supplied by the battery bank to the critical load, Fuel Cell and the non critical load remain disconnected during this interval of time as shown in fig 4.7.

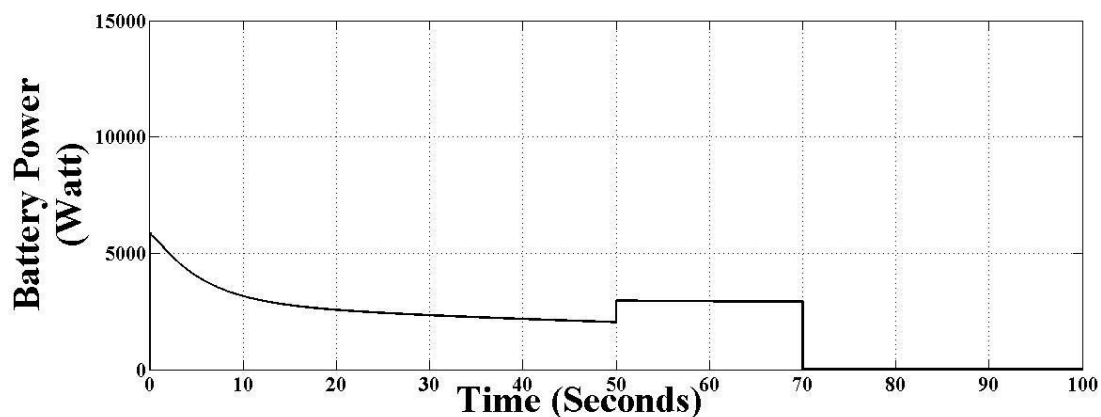


Figure 4.8 Power Supplied by Battery bank to the Load

From 70-100 sec. Fuel Cell and battery bank are both disconnected and power to the load is supplied only by the DC grid as shown in fig. 4.8. The power supplied by FC based microgrid and the DC grid to Critical and Non-Critical loads at various time intervals is shown in fig. 4.9 and 4.10 respectively.

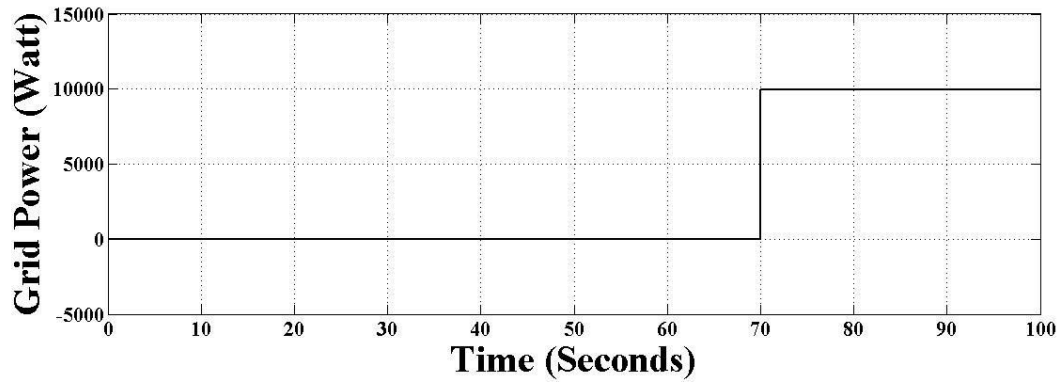


Figure 4.9 Power Supplied by Grid to the Load

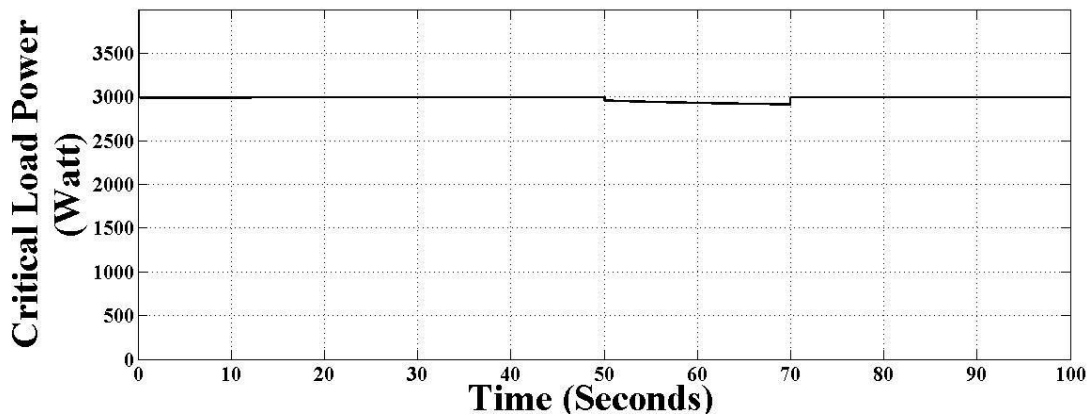


Figure 4.10 Total Power Supplied to Critical Load

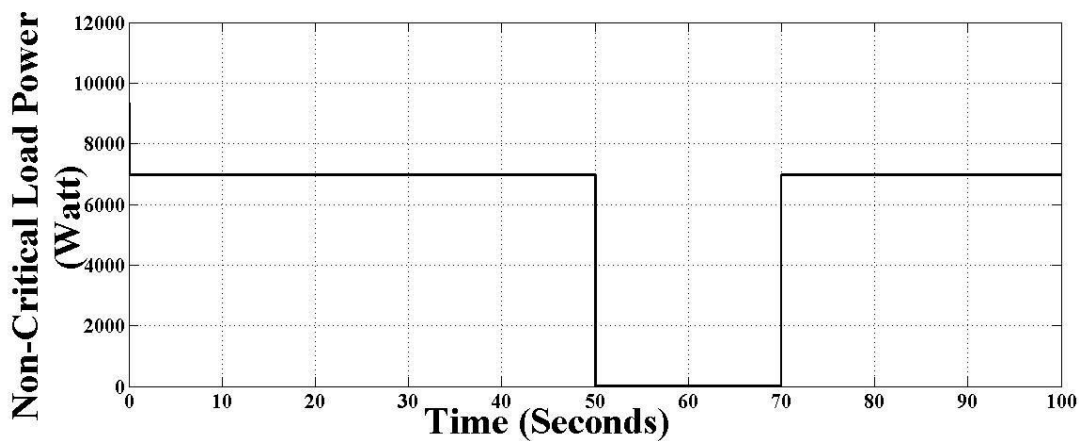


Figure 4.11 Total Power Supplied to Non-Critical Load

From the simulation results obtained in the fig. 4.6-4.10, it was observed that the critical and non-critical load was successfully delivered power from FC based microgrid. The total power delivered to the load was 10 kW and during the time interval of 50-70 sec. only battery bank was used to supply the critical load and the non-critical load was disconnected during this time interval. The current and power distribution shown in the table 4.3 and 4.4 show that there was successful power sharing between fuel cell, battery and DC grid.

Table 4.3
Current distributions of various Power sources and load

S.No.	Time Duration (sec.)	Fuel cell Current, I_{fc} (Ampere)	Battery Current, I_b (Ampere)	Grid Current, I_g (Ampere)	Critical load Current, I_{cl} (Ampere)	Non-Critical load Current, I_{ncl} (Ampere)
1	0-10	68.27	31.56	0	29.96	69.87
2	10-50	79.51	20.35	0	29.97	69.89
3	50-70	0	29.56	0	29.56	0
4	70-100	0	0	99.84	29.96	69.88

Table 4.4
Power distributions of various Power sources and load

S.No.	Time Duration (sec.)	Fuel cell Power, P_{fc} (Watt)	Battery Power, (P_b) (Watt)	Grid Power, P_g (Watt)	Critical load power, P_{cl} (Watt)	Non-Critical load power, P_{cl} (Watt)
1	0-10	6824	3153	0	2991	6974
2	10-50	7950	2034	0	2993	6978
3	50-70	0	2915	0	2913	0
4	70-100	0	0	9984	2992	6976

Chapter 5

Conclusions and Future Scope of Work

5.1 Conclusions

In this dissertation a comprehensive literature survey on various types fuel cell and their implementation in microgrid is studied. The fuel cell parameters like stack efficiency, stack voltage and current are studied in response to changing fuel flow rate when a DC motor is connected as load using Matlab/Simulink. It is observed that fuel cell efficiency starts decreasing when fuel flow rate is increased abruptly. The motor parameters like speed, electric torque, armature current are also observed and the values obtained after simulation are validated from the mathematical equations of the separately excited DC motor. A microgrid model using fuel cell along with battery and a low voltage DC grid is simulated to analyze the power sharing between battery and Fuel cell. The proposed fuel cell based microgrid system is simulated to cater the critical and non critical loads in grid connected mode and islanded mode of operation. The simulation results showing current and power distributions among grid, fuel cell and battery are found satisfactory.

5.2 Future Scope of Work

The future scopes of present research are stated below:

- (a) The present research is carried out considering a low voltage fuel cell based DC microgrid catering DC loads such as resistive loads and separately excited DC motor. This work could be extended to investigate the performance of same microgrid model when it is connected with AC rotational machines. The present microgrid model has to be modified by connecting inverter circuits to supply AC power to the AC loads for future studies.
- (b) The simulation work may be implemented to validate the efficiency of a proposed practical system of FC based microgrid before onsite installation.
- (c) The effects of transients in the fuel cell system due to severe short circuit faults at different points of microgrid may be investigated.

Research Publication: Malhotra D., Basak P. “Modelling and Simulation of Sample Fuel Cell and its Performance Analysis” *National Conference on Integrated Computational Techniques in Electrical Engineering, Thapar University, Patiala, 18-19 January, 2014.*

References

- [1] Kongwanarat N. and Limmeechokchai B. “Sustainable rural electrification in Thailand: analysis of energy consumption and CO₂ emissions” *International Conference and Utility exhibition on Green Energy for Sustainable Development, Pattaya, Thailand*, pp.1-7, 19-21 March 2014.
- [2] Sayigh A., Crueden A.J. “PEM Fuel cells” *Comprehensive energy fuel cell and hydrogen technology*, vol.4, June 2012.
- [3] Yunchang S., Zhaozheng S., Yiyun W. “Development situation and policy suggestion of Chinese renewable energy” *International Conference on Materials for Renewable Energy & Environment (ICMREE), Shanghai*, vol.1, pp.1-4, 20-22 May 2011.
- [4] Hartono B.S., Budiyanto Y., Setiabudy R. “Review of Microgrid technology” *International Conference on Quality in Research*, pp. 127-132, 25-28 June 2013.
- [5] Alibhai Z., Gruver W.A., Kotak D.B., Sabaz D. “Distributed Coordination of Microgrids using bilateral contracts” *IEEE international Conference on systems, man and cybernetics*, vol.2, pp. 1990-1995, 10-13 Oct. 2004.
- [6] Mingyan S., Ruiye L., Dianjun L.V. “Control Strategy of Voltage and Frequency for islanded Microgrid” *International Power Electronics and Motion Control Conference*, vol.3, pp.1074-1082, 2-5 June 2012.
- [7] Lassater R.H., “Smart Distribution: Coupled Microgrids” *Proceedings of IEEE*, vol.99, no.6, pp.1074-1082, June 2011.
- [8] Katiraei F., Iravani R., Hatziargyriou N., Dimeas A. “Microgrid Management” *IEEE Power and Energy magazine*, vol.6, no.3, pp.54-65, May- June 2008.
- [9] IEEE Standard for Interconnecting Distributed Resources with Electric Power System, IEEE Std. 1547.2-2008, 15 April 2009.
- [10] Redfern M.A., Al-Nasseri H. “Protection of Microgrids dominated by distributed generation using solid state converters” *IET 9th International Conference on Development in Power System Protection*, pp.670-674, 17-20 March 2008.
- [11] Conti S. “Analysis of distribution network protection issues in presence of dispersed generation” *Electric power research Journal*, vol.79, issue1, pp.543-566, June 2009.
- [12] Ke Jin, Xinbo Ruan, Mengxiong Yang, Min Xu “A Hybrid Fuel Cell Power System” *IEEE Transactions on Industrial Electronics*, vol.56, no.4, pp.1212-1222, April 2009.

- [13] Ellis M.W., Von Spakovsky M.R., Nelson D.J. "Fuel cell systems: efficient, flexible energy conversion for the 21st century" *Proceedings of IEEE*, vol.89, no.12, pp.1808-1818, Dec 2001.
- [14] Du Liming, Zhang Jun, Sun Liping "A Compact Fuel Processor integrated with 75kw PEM Fuel Cells" *International Conference on Electric Information and Control Engineering*, pp.1906-1910, 15-17 April 2011.
- [15] Zhao D., Blunier B., Gao F., Dou M., Miraoui A. "Control of Ultrahigh- Speed Centrifugal Compressor for the Air management of Fuel Cell System" *IEEE Transactions on Industry Applications*, vol.50, no.3, pp.2225-2234, May-June 2014.
- [16] Metz T., Paust N., Muller C., Zengerle R., Koltay P. "Micro Structured Flow Field for Passive Water Management in miniaturized PEM Fuel Cells" *IEEE 20th International Conference on Micro Electro Mechanical Systems*, pp.863-866, 21-25 Jan. 2007.
- [17] Xinhong Huang, Zhihao Zhang, Jin Jiang "Fuel Cell Technology for Distributed Generation: An Overview" *IEEE International Symposium on Industrial Electronics*, vol.2, pp.1613-1618, 9-13 July 2006.
- [18] Brunton J., Kennedy D.M., O'Rourke F., Coyle E. "Design of a single Alkaline Fuel Cell test bed" *International Conference on Environment and Electrical Engineering*, pp.53-56, 16-19 May 2010.
- [19] Lukas M.D., Lee K.Y., Ghezeli Ayagh H., "Development of a stack simulation model for control study on direct reforming molten carbonate fuel cell power plant" *IEEE Transactions on Energy Conversion*, vol.14, no.4, pp.1651-1657, Dec 1999.
- [20] Lengden M., Cunningham R., Johnstone W. "Tunable Diode Laser based Concentration Measurements of water vapour and methane on Solid Oxide Fuel Cell" *Journal of Lightwave Technology*, vol.31, no.9, pp.1354-1359, May 2006.
- [21] Yakbe H., Sakurai T., Sobue T., Yamashita S., Hase K. "Solid oxide fuel cells as promising candidates for distributed generators" *IEEE International Conference on Industrial Informatics*, pp.369-374, 16-18 Aug. 2006.
- [22] Ferrigolo F.Z., Dutra A., Farret A. "Inclusion of star-up effect in the electronic modeling of PEM fuel cells" *Power Electronic Conference*, pp.1108-1112, Oct. 2009.
- [23] Wang C., Nehrir M.H. "A physically-based dynamic model of solid oxide fuel cell" *IEEE Transactions on Energy Conversion*, vol.22, no.4, pp.887-897, Dec. 2007.

- [24] Elbakush E., Sharaf A.M., “A novel hybrid FC- Battery drive system for electric vehicles” *24th Canadian Conference on Electrical and Computer Engineering*, pp.001169-001174, 8-11 May 2011.
- [25] www.Fuelcelltoday.com/applications.
- [26] Lu Xueqin, Huang Fuzen, Liu Gang, Qiu Rongfu “The challenges of technologies for fuel cell and its application on vehicles” *IEEE International Conference on Power Electronics and Motion Control*, pp.2328-2333, 17-20 May 2009.
- [27] Obara S., Kudo K. “The Distribution design of PEM fuel cell cogeneration” *Fourth International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, pp. 873-880, 12-14 Dec. 2005.
- [28] Maeda K., Suzuki M., Aki H. “R&D and deployment of residential fuel cell cogeneration systems in Japan” *Power and Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st energy*, pp.1-5, 20-24 July 2008.
- [29] Kakigano H., Miura Y., Ise T., Momose T., Hayakawa H. “ Fundamental characteristics of DC microgrid for residential houses with cogeneration system in each house” *Power and Society General Meeting- Conversion and Delivery of Electrical Energy in the 21st energy*, pp.1-8, 20-24 July 2008.
- [30] Ovan V., Petrovcic J., Pirnat P. “A transportable dwelling container with in- built fuel cell cogeneration system” *18th Mediterranean Conference on Control and Automation*, pp.117-122, 23-25 June 2010.
- [31] Thanapalan K., Zhang F., Maddy J., Premier G., Guwy A. “ Design and implementation of on board hydrogen production and storage system for hydrogen fuel cell vehicles” *2nd International Conference on Intelligent Control and Information Processing*, vol.1, pp.484-488, 25-28 July 2011.
- [32] Bilal A., Benyoucef K., Miloud T.A., Ahmed K. “Solar hydrogen production for fuel cell use: Experimental approach” *2nd International Symposium on Environment Friendly Energies and Application*, pp.549-553, 25-27 June 2012.
- [33] Al-Ahmed A., Hossain S., Mukhtar B., Rahman S.U., Abualhamayel H., Zaidi J. “Hydrogen Highway: An Overview” *IEEE International Energy Conference and Exhibition*, pp.642-647, 18-22 Dec. 2010.
- [34] Cingoz F., Elrayyah A., Badawy M.O., Sozer Y. “Reliability and cost analysis of solar photovoltaic and fuel cell based microgrids” *29th Annual IEEE Applied Power Electronics Conference and exposition*, pp.3166-3173, 16-20 March 2014.

- [35] Jia J., Wang Y., Lian D. “Matlab / Simulink based- study on PEM fuel cell and battery hybrid system” *10th International Conference on Control, Automation, Robotics and vision*, pp.2108-2113, 17-20 Dec.2008.
- [36] Loc Nguyen Khanh, Jae-Jin Seo, Yun-Seong Kim, Dong-Jun Won “Power management Strategies for a Grid Connected PV-FC Hybrid System” *IEEE Transactions on Power Delievery*, vol.25, no.3, pp.1874-1882, July 2010.
- [37] Xunwei Yu, Xu She, Xiaohu Zhou, Huang A.Q. “Power management for D.C Microgrid enabled by solid state Transformer” *IEEE Transactions on Smart Grid*, vol.5, no.2, pp.954-965, March 2014.
- [38] Mishra S., Mallesham G., Sekhar P.C. “Biography Based optimal feedback for frequency regulation of a smart microgrid” *IEEE Transactions on Smart Grid*, vol.4, no.1, pp.628-637, March 2013.
- [39] Saitoh H., Abe M., Yashima W. “A proposal of emergency microgrid operation of distribution system after large scale disaster” *Humanitarian Technology conference IEEE Region*, pp.136-141, 26-29 Aug. 2013.
- [40] Samosir A.S., Anwari M., Yatim A.H.M. “Dynamic evolution control of interleaved boost dc-dc converter for fuel cell application” *IPEC*, pp.869-874, 27-29 Oct 2010.
- [41] Yuedong Zhan, Youguang Guo, Jianguo Zhu, Hua Wang “Design and analysis of control system of a Proton Exchange Membrane Fuel Cell directly connected with a DC Motor” *International Conference on Electrical Machines and Systems*, pp.1706-1710, 17-20 Oct. 2008.
- [42] Bizon N. “FC Energy harvesting using MPP tracking based on modified extremum seeking control” *Applied Energy*, vol.104, issue 4, pp.326-336, April 2013.
- [43] Eghtedarpour N., Ebrahim F. “Distributed charge / discharge control of energy storages in renewable energy based DC microgrid” *IET Renewable Power Generation*, vol.8, issue1, pp. 45-47, April 2013.

