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An Intelligent Power Management System for
Unmanned Aerial Vehicle Propulsion
Applications

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Abstract

Electric powered Unmanned Aerial Vehicles (UAVs) have emerged as a prominent aviation concept due to the advantageous such as stealth operation and zero emission. In addition, fuel cell powered electric UAVs are more attractive as a result of the long endurance capability of the propulsion system. This dissertation investigates novel power management architecture for fuel cell and battery powered unmanned aerial vehicle propulsion application. The research work focused on the development of a power management system to control the hybrid electric propulsion system whilst optimizing the fuel cell air supplying system performances.

The multiple power sources hybridization is a control challenge associated with the power management decisions and their implementation in the power electronic interface. In most applications, the propulsion power distribution is controlled by using the regulated power converting devices such as unidirectional and bidirectional converters. The amount of power shared with the each power source is depended on the power and energy capacities of the device. In this research, a power management system is developed for polymer exchange membrane fuel cell and Lithium-Ion battery based hybrid electric propulsion system for an UAV propulsion application. Initially, the UAV propulsion power requirements during the take-off, climb, endurance, cruising and maximum velocity are determined. A power management algorithm is developed based on the UAV propulsion power requirement and the battery power capacity. Three power states are introduced in the power management system called Start-up power state, High power state and Charging power state. The each power state consists of the power management sequences to distribute the load power between the battery and the fuel cell system. A power electronic interface is developed

with a unidirectional converter and a bidirectional converter to integrate the fuel cell system and the battery into the propulsion motor drive. The main objective of the power management system is to obtain the controlled fuel cell current profile as a performance variable. The relationship between the fuel cell current and the fuel cell air supplying system compressor power is investigated and a referenced model is developed to obtain the optimum compressor power as a function of the fuel cell current. An adaptive controller is introduced to optimize the fuel cell air supplying system performances based on the referenced model. The adaptive neuro-fuzzy inference system based controller dynamically adapts the actual compressor operating power into the optimum value defined in the reference model. The on-line learning and training capabilities of the adaptive controller identify the nonlinear variations of the fuel cell current and generate a control signal for the compressor motor voltage to optimize the fuel cell air supplying system performances.

The hybrid electric power system and the power management system were developed in real time environment and practical tests were conducted to validate the simulation results.

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Contents

Contents	i
List of Figures	vii
List of Tables	xiii
Nomenclature	xviii
1 Introduction	1
1.1 Research Background	2
1.2 Electric Propulsion and Power Management	3
1.3 Fuel Cell Control	4
1.4 Research Objectives	5
1.5 Control Approach	7
1.6 Overview of Dissertation	8
2 Literature Review	11
2.1 Literature Review	11

CONTENTS

2.2	Electric Propulsion Technology	12
2.3	Electric Propulsion in Aerospace Applications	14
2.4	Fuel Cell and Battery Hybrid Electric System	18
2.4.1	Hybrid System Power Management	19
2.5	Intelligent Power Management	25
2.5.1	Adaptive Neuro Fuzzy Control	26
2.6	Fuel Cells	27
2.6.1	Fuel Cell History	29
2.6.2	Fuel Cell Types	31
2.6.3	PEM Fuel Cell Development	35
2.7	PEMFC System Control	36
3	PEM Fuel Cell Systems and	
	Cathode Dynamics	41
3.1	PEM Fuel Cells	42
3.2	Cell Voltage	44
3.2.1	Open Circuit Voltage	44
3.2.1.1	Pressure Effect	45
3.2.1.2	Temperature Effect	47
3.3	PEM Fuel Cell Polarization	48
3.3.1	Exchange Current Density	48
3.3.2	Activation Loss	50
3.3.3	Ohmic Loss	51
3.3.4	Concentration Loss	51
3.3.5	PEM Fuel Cell Operational Voltage	53
3.4	Cathode Dynamics	55
3.4.1	Air Flow Rate	55
3.5	Air Supply System	57
3.5.1	Air Pressurization	57
3.6	Fuel Cell Net Power	58
3.6.1	Voltage Gain	59
3.6.2	Net Power Gain	59

4	UAV Propulsion Power	63
	Requirements	63
4.1	UAV Mission Profile	64
4.1.1	Long Endurance Mission	65
4.2	UAV Performance Requirements	66
4.3	Total Aircraft Weight	68
4.4	Take-off Performances	69
4.4.1	Rate of Climb	71
4.5	Aircraft Level Flight Operation	73
4.6	Mission Maximum Velocities	74
4.7	Propeller Efficiency and Motor Shaft Power	75
4.7.1	DC Motor and Propeller Matching	76
4.7.2	Mission Power Profile for Long Endurance Mission	78
4.8	Range of the Mission	79
5	Electric Propulsion System	83
5.1	Electric Propulsion System	84
5.2	Permanent Magnet Brushless DC motor	84
5.2.1	Operational Principals	85
5.2.2	Motor Control Approach	89
5.2.3	Motor Specifications	91
5.3	DC Bus Power	92
5.4	Battery Systems	94
5.4.1	Battery Characteristics	96
5.4.2	Battery Sizing	98
5.5	Power Converters	100
5.6	PEM Fuel Cell System	104
5.7	Simulation Models	105
6	Intelligent Power Management	107
6.1	Introduction	107
6.2	Power Management System	108
6.2.1	Start-up State	109
6.2.2	Charging State	110

CONTENTS

6.2.3	High Power State	112
6.3	Fuel Cell Power Conditioning Unit	114
6.3.1	Unidirectional Converter Voltage and Current Limits	115
6.4	BDC Voltage and Current	116
6.5	Operation Principle	116
6.5.1	Voltage Mode Controller	117
6.5.2	Current Mode Controller	118
6.6	Simulation	119
6.6.1	Finite State Machine Simulation	120
6.6.2	Start-up State Transitions	121
6.6.3	High Power State Transitions	122
6.7	Simulation Results	124
6.7.1	Case Study (I)	126
6.7.2	Case Study (II)	128
7	Fuel Cell Control and	
	Power Management	135
7.1	Fuel Cell System Control Approaches	136
7.2	Adaptive Control Strategy	140
7.3	ANFIS Controller Operation	141
7.3.1	Fuzzy Logic Decisions	143
7.3.1.1	Fuzzification Interface	143
7.3.1.2	Rule Base System	144
7.3.1.3	Fuzzy Inference Machine	145
7.3.1.4	Defuzzification Interface	146
7.3.2	Adaptive Process	146
7.3.3	ANFIS MATLAB Model	150
7.4	Compressor and Motor Models	153
7.4.1	Compressor Map	154
7.5	Simulations	156
7.5.1	ANFIS Results	157
7.5.2	Plant Results	162
7.5.3	Compressor Power Comparison	165

8	Power Converters Design and Control	169
8.1	DC Bus Voltage Regulation	170
8.2	Unidirectional Power Converter Topology	172
8.2.1	UDC Theory of Operation	173
8.2.2	Unidirectional Power Converter Design	175
8.2.2.1	Inductor Design	176
8.2.2.2	DC Bus Capacitance	179
8.3	Bidirectional Converter Topology	180
8.3.1	BDC Theory of Operation	181
8.3.2	Bidirectional Converter Design	182
8.3.2.1	BDC Boost Mode Operation	182
8.3.2.2	BDC Buck Mode Operation	185
8.3.2.3	Inductance	186
8.3.3	LV Side Capacitance	186
8.4	Pulse Width Modulation and Embedded Control	188
8.4.1	Microcontroller PWM Signal Control	190
9	Experiments, Results and Discussions	193
9.1	The Hybrid Electric Experimental Setup	193
9.2	Experiment (1): Start-Up State Test	194
9.2.1	Procedure	195
9.2.2	Results	195
9.2.3	Discussion	199
9.3	Experiment (2): High Power and Charging Power States Test	201
9.3.1	Procedure	201
9.3.2	Results	201
9.3.3	Discussion	203
10	Conclusion and Future work	207
10.1	Power Management	207
10.2	Fuel Cell Control	209
10.3	Potential Future Research	210

CONTENTS

A	Appendix A	213
A.1	Maximum Lift Coefficient	213
A.2	Wing loading	214
A.3	Thrust to weight ratio (T/W)	214
A.4	Lift to Drag ratio	216
	Bibliography	217

List of Figures

2.1	Viable energy options for primary power sources with flight durations, (Referenced from [1])	15
2.2	Fuel cell stack and subsystems	28
2.3	Fuel cell systems range of applications (Reproduced from the J. Larminie <i>et al</i>) [2]	32
3.1	PEM fuel cell structure	43
3.2	Effect of the air pressure	46
3.3	PEM fuel cell polarization curve	49
3.4	Effect of the activation loss	51
3.5	Simulink model of the PEM fuel cell	54
3.6	Effect of the cell temperature to the cell potential	55
3.7	Fuel cell net power variations with the pressure ratio	60
3.8	Optimum compressor power	61
4.1	Aircraft mission scenario	65
4.2	FC-UAV altitude variations during the long endurance mission	66

LIST OF FIGURES

4.3	FC-UAV speed variations during the long endurance mission	67
4.4	Aircraft rolling and airborne distance	70
4.5	Aircraft force distribution during the climb	71
4.6	Aircraft power required for different speeds	75
4.7	Propeller efficiency variation with the advance ratio during the take-off power mode	78
4.8	Propeller efficiency variation with the advance ratio during the cruise power mode	78
4.9	Propeller efficiency variation with the advance ratio during the maximum velocity power mode	79
5.1	Fuel cell and battery hybrid electric propulsion system	84
5.2	Permanent magnet brushless DC motor and the three phase inverter . .	86
5.3	Equivalent circuit of the motor	87
5.4	Torque vs Speed curve	88
5.5	PMBL DC motor control architecture	90
5.6	The simulation models of the PMBL DC motor and controllers	90
5.7	Motor speed controller	91
5.8	Motor current controller	91
5.9	PMBL DC motor and inverter drive	93
5.10	Equivalent circuit of the battery cell	97
5.11	Discharging curve of the battery	97
5.12	Battery SoC vs terminal voltage	98
5.13	Bidirectional converter developed in the Matlab Simpower System . . .	103
5.14	Unidirectional converter developed in the Matlab Simpower System . .	103
5.15	Horizon H-100 PEMFC system and controller	104
5.16	PEM fuel cell power variation with current	106
5.17	Hybrid power system developed in Matlab Simpower System toolbox .	106
6.1	Regulated hybrid power system	109
6.2	DC bus current variations during the mission	110
6.3	Power management system decision flow chart	111
6.4	Power flow during the Start-up state	112
6.5	Power flow during the Charging state	112

LIST OF FIGURES

6.6	Power flow during the high power mode	113
6.7	Boundary conditions for the operating modes	114
6.8	DC bus current distribution during the Start-up process	117
6.9	Voltage mode controller	119
6.10	Current Mode controller	120
6.11	Circuit diagram of the Start-up state	122
6.12	State machine developed for Start-up event	123
6.13	Simulink model for the Start-up state	124
6.14	DC bus voltage and power converters HV side current variations during the high power state	125
6.15	State machine for the high power state and the level flight operation . .	126
6.16	DC bus current variations during the mission (I)	127
6.17	Current distribution between the UDC and the BDC	128
6.18	DC bus current variations during the simulation	129
6.19	UDC HV side current variations.	129
6.20	BDC HV side current variations.	130
6.21	Fuel cell voltage variations	130
6.22	Fuel cell current variations	131
6.23	Battery SoC variations	131
6.24	DC bus current variations in mission (II).	132
6.25	UDC current variations in mission (II).	132
6.26	BDC current variations in the mission (II).	133
6.27	Fuel cell current variations in the mission (II).	133
6.28	Fuel cell voltage variations in the mission (II).	134
6.29	Battery SoC variations during the mission (II).	134
7.1	Simplified schematic diagram of the ANFIS controller and the Plant at time (t) and (t+1)	140
7.2	Network representation of the adaptive neuro fuzzy inference system . .	142
7.3	Normalized Battery SoC input membership functions	144
7.4	Normalized fuel cell current (I_{fc}) input membership functions	144
7.5	Non-trained fuzzy surface generated by the rule base (initial)	146
7.6	ANFIS controller	152

LIST OF FIGURES

7.7	Compressor and motor models with ANFIS controller	153
7.8	Compressor Map	156
7.9	ANFIS controller and Plant Models developed in MatLab Simulink . . .	157
7.10	Optimum compressor power during the mission (I)	158
7.11	ANFIS control signal for the compressor motor voltage variations	158
7.12	Trained fuel cell current membership functions of the ANFIS controller .	159
7.13	Trained ANFIS surface during the charging power state	160
7.14	Trained SoC membership functions of the ANFIS controller	161
7.15	Trained ANFIS control surface during the high power state	161
7.16	The compressor speed variation during the mission (I)	162
7.17	The compressor torque variation during the mission (I)	163
7.18	Required air mass flow rate for the mission (I)	164
7.19	Pressure ratio variation during the mission (I)	164
7.20	Actual compressor power (P_{com}) variation during the mission (I)	164
7.21	Actual compressor power adaptation to the optimum compressor power during the mission (I)	165
7.22	Fuel cell system net power output with the optimum compressor power	166
7.23	Fuel cell system net power output with the constant compressor power .	166
7.24	Fuel cell net power output comparison between the constant and the op- timum configurations	167
8.1	DC bus regulation process	171
8.2	Unidirectional converter circuit diagram	172
8.3	UDC current flow during the $Q1$ switch ON state	173
8.4	UDC current flow during the $Q1$ switch OFF state	173
8.5	Bidirectional converter circuit diagram	180
8.6	BDC current flow during the boost mode	181
8.7	BDC during the $Q2$ ON state	182
8.8	BDC during the $Q2$ OFF state	183
8.9	BDC current flow during the buck mode	186
8.10	LV side capacitor energy variation with time	187
8.11	Bidirectional converter developed for hardware set-up	188
8.12	Changes in duty ratio	189

LIST OF FIGURES

8.13	PWM signal duty ratio changes at the voltage control mode	190
9.1	Hardware set-up developed for experimentation	194
9.2	Polarization curves comparison between the fuel cell and the programmable power supply	195
9.3	Battery current variations during the Start-up state	196
9.4	Battery voltage variations during the Start-up state	197
9.5	DC bus voltage variations during the Start-up state	197
9.6	UDC LV side current variations during the Start-up state	198
9.7	UDC LV side voltage variations during the Start-up state	198
9.8	Battery current comparison during the Start-up state	200
9.9	Fuel cell current comparison during the Start-up state	200
9.10	Battery current variations during the high and charging states	202
9.11	Battery voltage variations during the high and charging states	202
9.12	Primary power source current variations during the high and charging states	203
9.13	Primary power source voltage variations during the high and charging states	203
9.14	Battery current comparison during the High power and Charging states	204
9.15	Fuel cell current comparison during the High power state	205
A.1	Aircraft rolling and airborne distance [3]	214
A.2	Flight path radius [3]	215

LIST OF FIGURES

List of Tables

2.1	Key milestones of the fuel cell history (Extracted from I. Eduardo [4])	31
3.1	PEM fuel cell system specifications	54
3.2	Optimum compressor power for different FC current	61
4.1	UAV Performance Requirements	68
4.2	UAV mass distribution	69
4.3	UAV Power Requirements	80
5.1	Motor angular velocities	89
5.2	Motor Specifications	92
5.3	DC bus power at different flying modes	94
5.4	Battery types and performance specifications [5]	96
5.5	Battery specifications	100
5.6	DC bus currents at the different flying modes	102
5.7	Simpower System PEM fuel cell system specifications	105
6.1	Operating modes of the power converters	119

LIST OF TABLES

7.1 Rule based system 145

7.2 Compressor Map Regression Coefficients [6] 156

7.3 Fuel cell current estimation parameters before and after training process 159

7.4 Battery SoC estimation parameters before and after training process . . . 160

8.1 UDC specifications 175

8.2 BDC specifications 184

8.3 BDC components specifications 188



Nomenclature

A	Electrode active area (cm^2)
C	Capacitance (F)
C_B	Bulk concentration of the reactant ($molcm^{-3}$)
C_S	Concentration of the reactant at the surface of the catalyst ($molcm^{-3}$)
D	Drag (N)
D_e	Diffusion coefficient (cm^2s^{-1})
E	Electrical potential difference (v)
J_{cp}	Compressor inertia (kg/m^2)
L	Lift (N)
L_a	Inductance of the motor windings (H)
M	Mach number

LIST OF TABLES

N	Flux of reactant
P	Power (W)
P_c	Cell power (W)
P_{com}	Compressor power (W)
P_{com}^{op}	Optimum compressor power (W)
P_{fc}	Fuel cell power (W)
Pr	Pressure (Pa)
R	Resistance (Ω)
R_a	Range of the aircraft (m)
R_{cm}	Compressor motor resistance (Ω)
S	Aircraft surface area (m^2)
T	Temperature (K)
T/W	Thrust to weight ratio
T_e	Motor torque (Nm)
T_r	Thrust (N)
T_{fc}	Fuel cell temperature (K)
V_c	Cell voltage (v)
V_{cm}	Compressor motor voltage (V)
V_{tf}	Aircraft velocity (ms^{-1})
W	Weight (N)
W/S	Wing loading (Nm^{-2})
$\dot{M}_{H_2}$	Hydrogen gas consumption rate ($mol s^{-1}$)

LIST OF TABLES

$\dot{N}_{O_2}$	Oxygen consumption rate ($mols^{-1}$)
ω_{cp}	Compressor speed (rad/sec)
τ_{cm}	Compressor motor torque (Nm)
c_f	Fuel consumption rate ($mols^{-1}$)
d_c	Compressor diameter (m)
i_{fc}	Fuel cell current (A)
k_{ct}	Compressor motor torque constant (Nm/A)
k_{cv}	Compressor motor voltage constant ($V/rad/sec$)

Greek Symbols

α	Charge transfer coefficient
δ	Diffusion distance (m)
η	Efficiency
γ	Pressure coefficient
λ	Fuel cell reaction stoichiometry
μ	Gaussian membership function
ω	Motor angular velocity (rad/s)
ψ	Dimensionless head parameter
ρ_∞	Air density (kg/m^{-3})

Acronyms

<i>ANFIS</i>	Adaptive Neuro Fuzzy Inference System
<i>BDC</i>	Bidirectional Converter
<i>BEV</i>	Battery powered Electric Vehicle

LIST OF TABLES

BoP	Balance of Plant
C_D	Drag coefficient
C_L	Lift coefficeint
D_t	PWM duty ratio
DC	Direct Current
FC	Fuel Cell
FCV	Fuel Cell powered Electric Vehicle
HEV	Hybrid Electric Vehicle
$HFCV$	Hydrogen Fuel Cell Vehicle
HV	High voltage
ICE	Internal Combution Engines
ISR	Intelligence, surveillance and reconnaissance
LV	Low voltage
n	Number of cells
PEM	Polymer Exchange Membrane
$PMBL$	Permanent Magnet Brushless Motor
PMS	Power Management System
PWM	Pulse Width Modulation
R/C	Rate of Climb
SoC	State of Charge
UAV	Unmanned Aerial Vehicle
UDC	Unidirectional Power Converter

Introduction

Electric propulsion has been emerged as a modern propulsion technology for both automotive and aviation sectors as the results of the advanced technological developments in electric power sources and motor drives. Fuel cell and battery based hybrid electric power architecture has a great potential to use in small scale aircrafts and in unmanned aerial vehicles (UAVs) due to the higher power and energy densities of the power plant. The hybrid electric technology used in the automobile applications can be applied to the unmanned aerial vehicle (UAV) and small scale manned aircraft applications due to the propulsion similarities in the both applications. The electric power sources hybridization for the aerial vehicles and optimizing the energy usage during the mission are emerging trends in the aerospace electric propulsion applications. In this scenario, the UAV's power management system involves in a vital role in the hybrid power sharing process. In this thesis, novel power management architecture is introduced to control the hybrid system power flow and a fuel cell controller is developed to optimize the fuel cell system performances. This chapter describes the research background, electric propulsion, fuel cell control, research objectives and control approach and overview of the dissertation.

1. INTRODUCTION

1.1 Research Background

The electric propulsion is an efficient energy conversion process which converts chemical energy into mechanical power without internal or external combustion. In most automobile applications, the electric power sources such as fuel cell system or battery are directly used to propel the motor drive. However, the hybrid configuration of the fuel cell system and the battery forms a power plant with high power and energy densities to provide the peak power demand and to operate longer period than the individual battery or a fuel cell system. The hybrid power plant with a Polymer Exchange Membrane (PEM) fuel cell and a Lithium Ion (Li-Ion) battery has emerged as the most convenient hybrid electric configuration to use in the automobile applications due to the technical advantages such as solid state energy transformation and compact design. In addition, the PEM fuel cell and the Li-Ion battery powered hybrid electric vehicles are promoted as an environment friendly transport solution. However, the fuel cell powered vehicles popularity is still far behind compared to the gasoline engine vehicles due to the technological drawbacks such as the high manufacturing cost of the fuel cells and the lack of hydrogen infrastructure facilities.

The fuel cell powered UAVs (FC-UAV)s and small scale aircrafts have developed by several research groups to expand the fuel cell technology into the aviation industry. The endurance capability of the UAV has improved considerably as the result of the efficient energy conservation process of the fuel cell electric propulsion system. In addition to that, the hydrogen fuel cell powered aircrafts are introduced as an environment friendly aviation concept due to stealth operation and minimum carbon emission during the mission.

Even though, the electric vehicles have shown superior performances in terms of energy conversion efficiency and as the emission free transport solution, the electric energy storage is a crucial factor for the electric vehicles popularity. Basically, the energy stored in the battery is directly proportional to the range of the electric vehicle. The electric vehicles are developed based on two technologies which are the battery powered electric vehicles and the fuel cell powered electric vehicles. At present, the battery powered electric vehicle's range is lower than the similar size gasoline engine vehicle or the fuel cell powered vehicle's range due to the low energy density of the battery system. In addition to that, the longer battery charging time is another constraint to

limit the pure battery driven vehicles. The fuel cell system has emerged as a higher energy density device that can generate the electricity on board as long as reactants are supplied. The world's first hydrogen fuel cell electric vehicle which was known as Electrovan was developed by General Motors in 1966 [7]. In 1990s, the PEM fuel cell technology was expanded due to the improvements in polymer membrane technology. As a result of that, the researches focused on the PEM fuel cell electric vehicles were dramatically increased [7]. The PEM fuel cell system has proved that longer operation compared to the battery driven vehicles. However, the PEM fuel cell system has low power density due to the slow reaction rate. Hence, there is a delay in responding to the load changes immediately. By considering all these advantages and disadvantages, the PEM fuel cell and Li-Ion hybrid electric vehicles (FC-HEV) were developed since early 1990s. In most fuel cell hybrid electric vehicles, the PEM fuel cell system operates as the primary source and the Li-Ion battery operates as the secondary power source. The fuel cell hybridization with the battery eliminates the effects of the fuel cell transient delay to the propulsion system performances. In addition, the battery provides the supplementary power during the high load power demand and supplies the power required for fuel cell system's auxiliary devices. The PEM fuel cell system's power capacity can be downsized significantly by varying the battery power capacity. The fuel cell system and the battery hybridization process involve several engineering challenges and still a developing concept in power electronic domain.

1.2 Electric Propulsion and Power Management

The fuel cell hybrid electric propulsion system is mainly consisted of a PEM fuel cell, a Li-Ion battery and a permanent magnet brushless (PMBL) DC motor and a three phase inverter. The PMBL DC motor has advantages such as high efficiency, high speed range and better speed versus torque characteristics to improve the propulsion system performances [8]. The PEM fuel cell operates as a high energy density device and provides the propulsion power as long as hydrogen gas is available in the storage. The Li-Ion battery is the higher power density device and supplies the propulsion power for a limited period. The unidirectional boost converter and the bidirectional buck/boost converter integrate the power sources into the propulsion system.

1. INTRODUCTION

In most hybrid electric propulsion applications, the power sources are integrated into the propulsion system through a power electronic interface to control the hybrid system power flow. A power management system is required to generate the decisions for the power electronic interface. The power management algorithm is developed by considering the propulsion power requirements and the power source limitations. The power management system decisions are implemented by controlling the DC/DC power converter's voltage and current outputs. Many researchers have introduced the power management methodologies such as PI controllers, adaptive controllers, optimal controllers, fuzzy logic controllers, etc to improve the hybrid system power sharing strategy. The main purpose of the power management system is to decide the amount of power shared with the each power source and to determine the power splitting sequences of the hybrid power plant based on the power demanded by the propulsion system. Most commonly, the power sources are hybridized as unregulated or regulated hybrid power architectures. In the regulated power architecture, the DC bus voltage and the current are controlled by varying the unidirectional converter and the bidirectional converter Pulse Width Modulated (PWM) signals. The controllability of the current flow is the main advantage of the regulated hybrid system. In addition, the bidirectional converter can charge the battery during the low propulsion power demand. However, the regulated architecture components such as the unidirectional converter and the bidirectional converter add extra weight to the propulsion system. Furthermore, the unidirectional and the bidirectional converters internal losses reduce the hybrid system energy efficiency. However, the regulated hybrid architecture shows more benefits than the unregulated architecture in terms of lower battery size, weight and the capacity. Therefore, the power management system with the regulated hybrid power architecture can control the performance variable such as current and voltage and hence power.

1.3 Fuel Cell Control

In the hybrid electric power architecture, the control of fuel cell performances is important to achieve the optimum power output from the fuel cell system. Researchers have investigated the fuel cell control based on the three main approaches which are

geometrical variables, operational variables and performances variables. The geometric parameters decide the physical properties of the fuel cell such as the size, reactants flow paths and electrode thickness etc. The fuel cell main operational variables are cell humidity, reactant pressures, reactants flow rates and the temperature of the fuel cell. The fuel cell performance variables such as cell efficiency, current and cell voltage are also used to optimize the cell performances. The researchers revealed that the PEM fuel cell system performance variables and operational variables are interrelated and changes in one variable affect to the entire fuel cell performance. In most research publications, the effects from the performance parameters and the operational parameters to the fuel cell performances were investigated due to the considerable impact caused by these parameters. For an example, the fuel cell air supplying system control is vital in the performance optimization process due to the large portion of the fuel cell power is consumed by the air compressor. In the literature, the most of the researchers have been proposed the control methodologies in steady state and dynamic state conditions to control the performance and operational variables. In the dynamic state, the fuel cell system performances show nonlinear characteristics and hence nonlinear control technique are used.

1.4 Research Objectives

This research has multiple objectives related to the hybrid system design, the power management and the fuel cell system performance optimization. The research is mainly focused on the development of the power management architecture for the PEM fuel cell and the Li-Ion battery driven UAV propulsion application. The main objective is divided subcategories as follows;

- Identify the representative mission profile for the UAV.
- Determine the propulsion power requirement for the UAV mission.
- Define the PEM fuel cell and Li-Ion battery hybrid system power requirements based on the propulsion power requirements (System sizing).
- Design and synthesize the power management system for hybrid system power sharing strategy.

1. INTRODUCTION

- Define the fuel cell system performance optimization process.
- The verification of the power management system performances through the real time implementation of the hybrid system.

The small scale UAV's propulsion power requirement need to be investigated based on the UAV aerodynamics. The propulsion system power demands during the take-off, the climb, the cruising and the endurance will be determined. In this thesis, the aircraft performance requirements are defined based on the proposed mission and the critical parameters analysis are conducted to obtain the minimum propulsion power requirements for the different flying modes.

The fuel cell and the battery hybrid system specifications are determined based on the propulsion power requirements. The total power of the fuel cell system and the battery must be sufficient during the peak power demand of the propulsion system. The required PMBL motor specifications are determined and the motor controller developed to respond to the operator's command. Initially, the PEM fuel cell and the Li-Ion hybrid electric power system is developed in Matlab Simpower system simulation environment and as the second stage of the research, a hardware setup is developed to verify the proposed power management system.

A power management algorithm is developed to decide the operating power sequence of the hybrid power system. The proposed power management system initially controls the fuel cell system's start-up process which requires encountering the slow electrode reactions. During the start-up process, the fuel cell system auxiliary power devices such as the air compressor and the cooling pump are required to start before the fuel cell generates the electricity. Then, the hybrid propulsion system can operate in another two power stages such as high power and the battery charging power. The high power state is required to operate in hybrid configuration to respond the high load power demand during the aircraft take-off, the climb and the maximum velocity flying modes. The battery charging state is needed to charge the battery during the low propulsion power demand such as the cruising and the endurance flying modes. Therefore, the power management system is required to control the propulsion power distribution between each power source.

In addition to the power management of the hybrid system, the fuel cell's air supply system controller is introduced to achieve optimum power output from the fuel cell

system. The fuel cell current is considered as a performance variable and hence the fuel cell power output can be optimized by controlling the air supplying system as a function of the fuel cell current. The changes of the air supply system pressure and the flow rate minimize the cell voltage loss caused by the oxygen starvation. The proposed intelligent power management architecture is consisted with the hybrid system power management system for propulsion power distribution and the fuel cell air supplying system controller for fuel cell performance optimization.

As the implementation framework of this research, the bidirectional and the unidirectional power converters are developed to validated the simulation results. The non-isolated PWM controlled power converters are developed and the microcontroller based embedded system is used to generate the power converters switching sequences. The power management decisions were represented as the state machine sequences in the microcontroller program and at the relevant operating power state, the DC/DC power converter operating modes were changed to the current control mode or voltage control mode as defined in the power management algorithm. The research objectives were clearly defined and implemented throughout the research and results were obtained as expected.

1.5 Control Approach

In the literature, most commonly the hybrid system's power management techniques have been developed by ignoring the fuel cell system operational variables such as temperature, air supply pressure, flow rate and humidity. The fuel cell control techniques are discussed separately as the steady state analysis. However, the hybrid system power management and the fuel cell control technique are interrelated to each other in terms of operational variables and the performance variables. The control approach introduced in this research focused on the hybrid system control at the dynamic state. The proposed power management system controlled the fuel cell system current which was considered as the fuel cell performance variable. Based on the controlled fuel cell current, the fuel cell system air supplying system was controlled to achieve the optimum performances. Therefore, the power management architecture facilitated the control background for the fuel cell operational parameter which was the fuel cell air

1. INTRODUCTION

supply optimization process. The combination of the hybrid system power management with fuel cell air supplying control created the novel control architecture which had not been considered by many researchers.

The referenced model was developed to obtain the maximum net power output from the fuel cell system. The fuel cell system cathode dynamics were analyzed and identified the effect of the oxygen concentration to the fuel cell voltage output. The operational losses associated with fuel cell voltage were minimized by controlling the air pressure and the air flow rate. Therefore, the optimum pressure ratio which generated the maximum power from the fuel cell for a specific current was obtained and based on the desired optimum pressure ratio, the compressor power consumption was determined. The fuel cell air supplying system's optimum compressor power was represented as a function the fuel cell current. This function was used as the referenced model for the adaptive control process introduced in intelligent power management section.

The adaptive controller which could learn from the system output and trained the system input parameters to achieve desired target or referenced function showed great potential to apply in the real time system which needed optimized output. Adaptive neuro fuzzy inference system (ANFIS) controller showed similar characteristics in terms of nonlinear adaptability to the unknown referenced model. The main advantages of the ANFIS based control architecture were the dynamic adaptability to the nonlinear system and ability to define the approximated initial conditions for the fuzzy training process based on fuzzy logic rules. In the fuel cell control application, the ANFIS controller was used to adapt the fuel cell compressor power output to the optimum value obtained in the referenced model. This control approach could dynamically control the fuel cell air supplying system based on the fuel cell current determined by the power management system.

1.6 Overview of Dissertation

In this dissertation, the investigations on the hybrid electric power system and its power management stages are included. The power management concept and the fuel

cell control technique were combined and introduced a novel control architecture for the hybrid electric power system.

In the Chapter (2) of the dissertation, the literature reviews of the electric UAVs, hybrid system power management and the fuel cell control are described. The background of the hybrid electric propulsion and its applications are discussed in the chapter (2). The theories of the fuel cell and the cathode dynamics are analyzed in the chapter (3) and obtained the optimum operational power for the fuel cell air supplying system. These derivations are used in chapter (7) for the fuel cell performance optimization process. In the chapter (4), the UAV propulsion power requirements during the take-off, the climb, the cruising, the endurance and the maximum velocity modes are obtained from the aerodynamics derivations. The aircraft performance requirements are defined for an intelligence, surveillance and reconnaissance mission and conduct the critical parameter analysis for the mission requirement. Based on the propulsion power requirements, the propulsion system and the hybrid electric power plant performance specifications are defined in chapter (5). The PMBL DC motor, the motor controller with an inverter, the DC/DC power converters, the PEM fuel cell system and the Li-Ion battery are the main components discussed in chapter (5). The proposed power management system is introduced in chapter (6). The attributes of the power management algorithm are described and the simulation results are illustrated in chapter (6) to identify the power management system performances. In chapter (7), a fuel cell air supply system controller is developed based on the results obtained from the power management system. An adaptive controller with online learning and training capabilities is introduced to control the fuel cell air supplying system based on the optimum compressor power derived in the chapter (3). The unidirectional and the bidirectional power converters theories and designing stages are discussed in the chapter (8). The hybrid electric system was tested in real time environment and results are compared with the simulation in chapter (9). The project conclusions and future works are described in chapter (10).

1. INTRODUCTION

Literature Review

2.1 Literature Review

Nowadays, the electric propulsion and its applications are expanded not only in automobile industry and stationary power grids but also in aviation industry. The electric propulsion technology is being developed since the invention of the electricity. The English physician and a philosopher Dr. William Gilbert used the term 'Electricity' for the first time in history when he was analyzing the relationship between magnetism and electricity in 1600. The electricity related researches passed the key milestones such as invention of Michael Faraday's electric motor in 1821 and Thomas Alva Edison's lightbulb in 1879. Concurrently, an automobile developer, Hendry Ford developed his gasoline powered automobile in 1896. Henry Ford and Edison collaborated to develop electric vehicles since 1896 [9]. In 1891, the first successful electric automobile was built in the United States by William Morrisson [9]. The electric vehicles were popular as the results of the clean, silent and simple operation during the primary stage of gasoline automobile industry. Surprisingly, in 1900, almost 28% of the cars manufactured in the United States were powered by electricity [9]. As the results of the rapid development in internal combustion engines (ICE)s technology and due to the constraint

2. LITERATURE REVIEW

on electric energy storage, the electric vehicle technology was diminished until it re-emerged in early 1990. In past two decades, researchers and policy makers investigated the alternative energy solution for the conventional gasoline engine due to the concern on climate change, pollution and unstable and expensive foreign oil supply [7]. The most research outcomes were alongside with national renewable energy policy which promoted sustainable energy solutions. For an example, the United States federal government introduced the Alternative Motor Fuel Act of 1988, Clean Air Amendments of 1990 and Energy Policy Act of 1992. As the results of that, the investigations on the electric vehicles were increased as an alternative for the road transportation. Research publications appeared with explanations and suggestions on future economic and environmental impacts caused by the alternative transport solutions. Life cycle assessment (LCA) of the electric vehicle technology which includes vehicle manufacturing cost, fuel production, transport cost, vehicle operational, maintenance cost, disposal and recycling cost throughout the vehicle life time exposes the future potentials of the electric vehicle industry. Analysis show that, as a sustainable transport solution, the hydrogen powered fuel cell vehicles have the highest potential to dominate the future automobile and aviation industries [7].

2.2 Electric Propulsion Technology

Investigations on electric vehicle technologies such as hybrid electric vehicles (HEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCV) are accelerated in a broad aspect since early 1990s. These propulsion technologies show advantages as well as some disadvantages over the conventional gasoline engines and thus related publications are emerged with the analysis regarding cost effectiveness, environmental concern, lifetime evaluations and leading technology. In terms of cost effectiveness of the electrical vehicle technology, the vehicle manufacturing cost, range and fuel cost are considered. In addition to that, the environmental impacts are determined based on air pollution and greenhouse gas emissions by vehicle production process and while vehicle on operation. Pistoia in [7] conducted successful life cycle assessment between the hydrogen fuel cell vehicle (HFCV) and the gasoline vehicle (ICEV). It has described that the energy sources used to generate the electricity such as nuclear, fossil fuel or

renewable energy for the vehicle manufacturing process have considerable impact on production cost and environment. If the electricity is generated by using 50% nuclear energy and 50% renewable energy, the HEVs and BEVs productions are competitive than the FCVs in terms of cost effectiveness and the environmental impacts [7]. If the fossil fuel is used more than 50% to generate the electricity, the production cost and the environmental impacts are fairly low in HEVs and the HFCVs will be an expensive solution [7]. Based on the Pistoia analysis in [7], it has revealed that, during the fuel processing cycle, the HFCVs manufacturing process is the main contributor of the energy consumption and the greenhouse gas emissions (GHG) due to the hydrogen extraction. However, when it comes to the vehicle operational cycle, the ICEV energy consumption and the GHG emissions are higher than the HFCV. Finally, the overall energy consumption of the HFCV is 2.3 times less than the ICEV and the overall GHG emissions of the HFCV 2.6 times lower than the ICEV [7].

The hydrogen FCV combines the features of the BEV such as zero emissions, high efficiency, silent operation and features from the ICE vehicles such as long range, long life and fast refuelling time [7]. In addition to that, the recent investigations conducted by Sun *et al* [10] revealed that the fuel economy of the FCV which is 57 miles per gasoline-equivalent gallon (mpgge) is extremely high compared to the similar size gasoline internal combustion engine which has 20.1 mpg fuel economy. These figures clearly show that range and endurance capability of the vehicle have considerably improved by employing the fuel cell system.

In order to achieve cost effective and sustainable propulsion technology, hybrid electric power configurations have developed with multiple energy storage or multiple energy converting devices such as battery/ ultracapacitors and fuel cell/ battery power plants. The hybrid combination is mostly consisted with a higher power density device and a higher energy density device. The fuel cell alone powered vehicle disadvantages such as heavy bulky fuel cell power unit which has low power density, slow responses from the fuel cell system and long start-up time can be eliminated or minimized by the secondary power source [5]. The importance of the fuel cell vehicle technology is not only depended on the cost of the vehicle but also technical advantages such as stealth mode operation and long endurance capability in military vehicles applications. The fuel cell powered small scale aircrafts and unmanned aerial vehicles (UAVs) are emerging as a

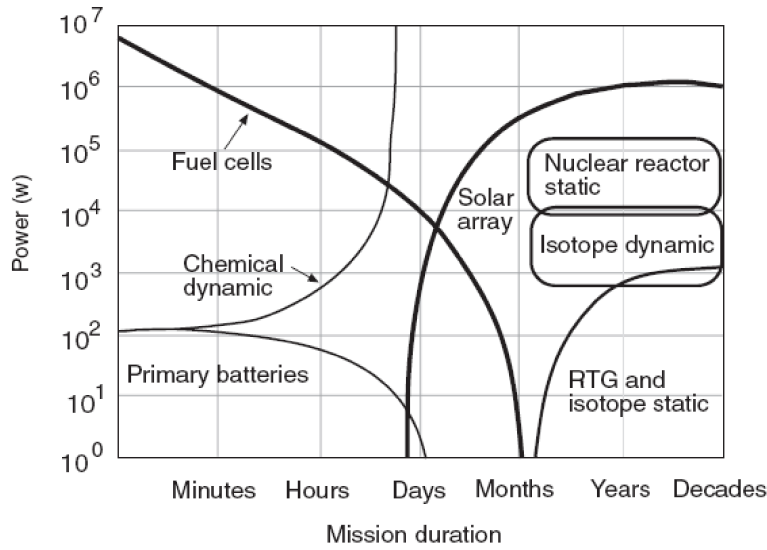
2. LITERATURE REVIEW

new aviation industry due to the long endurance capability and the stealthy operation of the fuel cell hybrid electric propulsion system.

2.3 Electric Propulsion in Aerospace Applications

The United State National Research Council (NRC) published a report in year 2000 describing the future unmanned aerial vehicle designs and propulsion technologies [1]. This report introduced a long term research plan on UAV technology for the United States Air Force (USAF). The proposed UAVs propulsion technologies show considerable improvements in aircraft fuel economy and long endurance capability. Figure 2.1 shows the energy options for primary power source with the flight duration [1]. The fuel cell has high energy capacity compared to the primary batteries and the operational period can be varied from minutes to months. The solar energy is another competitive energy source for the aviation sector which can supply the propulsion power for decades. However, the specific power density (W/kg) of the solar panel is low and hence the aircraft climb and take-off power can not be achieved in shorter time period with available solar panel technology. Therefore, the fuel cell is emerged as a viable hydrogen energy converter for the long endurance aircrafts with higher power density. Sehra A.K. *et al* [11] carried a feasibility study about the fuel cell power plants which can use for small aircraft propulsion system and as a Auxiliary Power Unit (APU) in large - scale commercial aircraft. Sehra A.K. *et al* [11] revealed that the fuel cell powered automotive propulsion system can be used to power the small scale aircraft. In addition to the long endurance capability of the hydrogen fuel cell powered aircraft, zero emissions, simpler power system, lower maintenance cost and stealth operation are the major benefits. The fuel cell powered aircrafts main propulsion challenges are low power to weight ratio of the fuel cell power plant and design constraints on hydrogen storage [11]. In addition to that, safe hydrogen-fuelling infrastructures are necessary to expand the fuel cell aircraft concept.

The National Aeronautics and Space Administration (NASA) has conducted preliminary study on 60kW fuel cell powered light weight aircraft propulsion system performances and published in [12]. In year 2003, Freeh J. E. *et al* [13] in NASA's Glenn



Note: RTG = radioisotope thermoelectric generator

Figure 2.1: Viable energy options for primary power sources with flight durations, (Referenced from [1])

Research Center (GRC) analyzed the fuel cell powered small aircraft power distribution during take-off period and cruising period. A comparative assessment was done between the reciprocating engine and the fuel cell and battery powered hybrid electric small aircraft that needed $60kW$ peak propulsion power. Freeh J. E. *et al* [13] analytically predicted that the advanced PEM fuel cell system can improve the aircraft range by 12.5% compared to the reciprocating engine. The applicability of the direct electric power train to the light aircraft was tested in this project and proved that the PEM fuel cell system with liquid hydrogen can exceed the range completed by the reciprocating engine aircraft. However, authors in [12] suggested that payload capacity, propulsion system weight, hydrogen fuel storage and power management distribution should be investigated in future researches.

The small scale PEM fuel cell powered long endurance aircraft was conceptually designed by Bradley T. H. *et al* [14] in Georgia Institute of technology in 2006. The conceptual aircrafts were designed based on two design approaches which were aircraft design for optimal energy density and aircraft design for optimal range and endurance. The aircraft design based on the optimal energy density was focused on sizing the hydrogen storage. Results found that the aircraft design which was optimized for the range and the endurance shows best performances such as climb performances, smaller

2. LITERATURE REVIEW

aircraft, long endurance and long range than the aircraft designed for optimal energy density [14].

In addition to conceptual design, T.H Bradley *et al* [15] built an experimental fuel cell UAV (FC-UAV) as a demonstrative aircraft. The results were published in [15] and [16] as the first ever fuel cell UAV related publications available in public domain. The FC-UAV propulsion system was consisted of the PEMFC system which had 500W power and the compressed hydrogen cylinder with 31MPa supply pressure. The FC-UAV was tested in level flight operating condition and take-off flight operating condition. It has identified that during the take-off period, the fuel cell power plant supplied the maximum power 323W for the propulsion system. During the take-off period, fuel to propulsive power efficiency was 14%. Throughout the cruising period, the propulsive power efficiency was 18%. T.H Bradley *et al* [15] concluded that the FC-UAV's fuel to propulsive efficiency is 18% which is higher than the same size, 2-stroke, 500W combustion engine UAV which has 13% propulsive efficiency [15].

In 2008, Boeing Research and Technology Europe (BR & TE) [17] developed a manned fuel cell powered small scale aircraft to demonstrate the environment friendly aviation technology. This was the first ever manned aircraft flew in aerospace with fully electric propulsion system. A small two seater airplane was powered by the PEM fuel cell system and the Li-ion battery hybrid configuration and propelled by the permanent magnet brushless (PMBL) DC motor. Lapena-Rey N. *et al* investigated the steady-state and the dynamic operating conditions of the fuel cell system and the battery hybrid electric system [17]. They have proved that the fuel cell has capability to supply the propulsion power longer period than the mission duration without considerable fuel cell performances degradation. The fuel cell system performances during the peak power demand were analyzed and identified the appropriateness of the fuel cell system for aerospace propulsion. The fuel cell system was tested in different orientation to verify the safe operating angles. There was no cell fluidic balance problem during the angular operations and hence the fuel cell system operated within the safe limits. The pre-flight analysis was successfully conducted with the hybrid electric propulsion system and verified to integrate the propulsion system into the airframe.

An unregulated and a regulated hybrid power architectures for the fuel cell aircraft were developed and tested by the Boeing Research and Technology Europe and results were published in [18]. In the unregulated architecture, the fuel cell and the battery

were connected directly to the propulsive motor. In the regulated hybrid configuration, the PEM fuel cell system was connected to the boost converter and controlled the hybrid system power flow. A power management and distribution box (PMAD) was developed to share the load power between the fuel cell system and the battery. A state machine was developed to control the operating sequences of the hybrid system. It has revealed that, due to the simplicity of the unregulated architecture, the reliability was higher in the unregulated configuration over the regulated architecture [18]. In addition, the efficiency of the unregulated hybrid system was higher than the regulated system due to the absence of the DC/DC power converters losses [18]. In the regulated hybrid electric configuration, the battery power requirement was lower than the unregulated system [18]. Due to the controllability of the regulated system power flow, the battery capacity could be minimized and hence size and weight of the battery also reduced. In addition to that, the regulated hybrid system has shown longer period of operation than the unregulated configuration for a certain power level [18]. The analysis conducted by [18] show that the regulated hybrid configuration has more benefits than the unregulated architecture in terms of the energy usage. However, the Boeing research group has selected unregulated architecture for their fuel cell demonstrator airplane which only considered level flight operation. They have ignored the battery energy saving which extends the endurance capability and also increases the available aircraft power for climb mode operation.

ENFICA-FC (ENvironment Friendly Inter City Aircraft powered by Fuel Cells) is an another fuel cell powered aircraft project funded by the European commission to validate the fuel cell propulsion for intercity aircraft [19]. Romeo G. *et al* [19] conducted a preliminary survey to identify the suitable airplane which needed low power at low velocity during the level flight operation. In addition to that, the hybrid electric system components such as the brushless motor, the fuel cell system, the battery pack and the power converters were placed into the airframe and identified the changes in the aircraft's center of gravity. In 2010, Romeo G. *et al* published the ENFICA-FC project progress in [20]. The optimized propeller design in ENFICA-FC aircraft achieved 87% efficiency. The regulated hybrid power architecture was selected with the DC/DC power converters to connect the fuel cell system and the battery into the propulsion system. The high energy density hydrogen storage improved the aircraft performances even better than the piston engine powered aircraft [20]. However, the positioning of

2. LITERATURE REVIEW

the power plant and propulsion system components varies aircraft center of gravity hence the aircraft stability is compromised with the improved performances.

The fuel cell powered aircraft concept was experimentally developed and performances were validated by several researches groups such as Boeing research and technology, Georgia Institute of technology and U.S. Air Force Research Laboratory (AFRL). The fuel cell and the battery hybrid electric configuration were common for most fuel cell power aircrafts. The hybrid electric configuration improves the aircraft take-off and climbing capabilities and furthermore the regulated hybrid architecture shows additional performances such as long endurance capability.

2.4 Fuel Cell and Battery Hybrid Electric System

In contrast to the BEVs, the fuel cell hybrid electric vehicles (FCHV)s have no historical background more than two decades. The FCHVs are commercially available since late 2000s. Almost all the fuel cell vehicles developed for commercial purposes by the major vehicle manufacturers such as Honda, Toyota, Nissan etc were included the PEM fuel cell (PEMFC) and the Li-Ion battery hybrid electric configuration into their fuel cell vehicles. In automobile aspects, the large number of publications related to the fuel cell and battery hybrid system suitable for future automobile applications have published since late 1990s.

The power sources hybridization process needs more mechanical and electrical engineering involvement than the simple BEV electric circuit. In the developing stages of the fuel cell hybrid electric power system, the electric motor is selected to meet the wide range of the power demand. The researchers have investigated various kind of hybrid configuration suitable for propulsion applications in automobile and aviation sectors. Mainly, the hybrid power architecture is divided into regulated and unregulated categories depending on the power converters involvement.

The PEM fuel cell system is allowed to operate within the optimal power region while the battery is operated as the backup power source [5]. The researchers have been introduced the different kind of power control methodologies to optimize the hybrid system performances. In automobile sector, the power and energy management of the hybrid system have been widely addressed with the control methodologies such as optimal

control, PI control, fuzzy logic control, adaptive control and generic algorithms etc to optimize the hybrid system performances. However, a proper power management system is necessary to distribute the load power demand between the battery and the fuel cell system.

Dougal R.A. *et al* in [21] analyzed the regulated and unregulated hybrid power systems to identify the advantages and the disadvantages in each configuration. The unregulated hybrid system showed smooth operation in DC bus voltage and minimum internal power losses [21]. As the main disadvantage of the unregulated configuration, the maximum voltage level of the battery was limited by the FC system. As another disadvantage, the load power distribution was depended on the fuel cell and the battery internal resistances. Dougal R.A. *et al* [21] revealed that the regulated hybrid system weight was increased 13% compared to the unregulated hybrid system by the additional weight of the power converter. However, the battery size can be minimized by the DC/DC power converters regulation process. In the unregulated architecture, the FC system operates below its maximum power output capabilities. When the battery charge is decreased, the battery voltage level reduces and the FC operates in maximum power to supply the total power demand. However, in the regulated hybrid power architecture, the battery and the fuel cell power capacities can be downsized as the results of the regulation process.

2.4.1 Hybrid System Power Management

The main objective of the power management is to supply the propulsion power demand while optimizing the power sources operating efficiencies. In the regulated hybrid power architecture, the DC/DC power converters control the power flow between the fuel cell and the battery.

Corbo P. *et al*[22] compared the fuel cell and the battery hybrid system power flow by using two different power control methodologies. The hybrid system was consisted of a fuel cell system, a unidirectional converter, a bidirectional converter, an inverter and a battery. The power management strategies were defined to supply steady-state energy by the FC system and the battery supplied the dynamic energy. The power controller main objective was to control the bidirectional converter operating modes under the buck, boost or shut down according to the power status of the fuel cell and the battery.

2. LITERATURE REVIEW

Corbo P. *et al* [22] defined nine different voltage status for the bidirectional controller to decide the operating mode. The control of bidirectional power converter gave the opportunity to charge or discharge the battery at the appropriate power stages of the hybrid system. In the first control method, the FC system has operated as a power leveling source which means that the power converter fixed the power output at average power level of the driving cycle. In the load leveling method, the battery system contributed 22% energy from the total energy demand. The load following method allowed the FC system to operate in different power mode instantaneously by following the load power demand. In this method, the battery contribution was 8% out of total energy demand. The results showed that the battery capacity can be reduced in the load-following method.

Dougal R.A. *et al* introduced the adaptive control strategy in [23] for the active hybrid system. The adaptive control strategy was developed to split the power between two power sources and varied the FC output current set point according to the battery state of charge (SoC). The battery voltage, battery current and FC current were the inputs signals and a state machine decides the operating mode of the hybrid system. The duty ratio of the DC/DC power converter was the control signal and a proportional and an integral (PI) controller were used for the adaptation process. The PI controllers regulated the duty ratio according to the state machine status. The simulation and experimental results of this control strategy showed that power sharing between the power sources has improved by adapting the duty ratio of the power converter to achieve the desired FC operating condition. However, this analysis was limited to the five operating modes of the hybrid system and the adaptive control strategy did not consider the parasitic losses associated with the FC system during the state changes of the state machine. The FC system efficiency was not optimum during the state changes and the maximum net power output deviated from the optimum value. In [24], Dougal R.A. and Jiang Z. programmed the state machine into a microcontroller and developed a digital controller to generate the Pulse Width Modulated (PWM) signals.

Jeong K.S. *et al* [25] introduced a rule based fuzzy logic control system to distribute the load power. The fuzzy logic rules decide the FC system operating power based on the battery SoC and the load power variations. The regulated hybrid power architecture

was developed to identify the hybrid system efficiency at different battery power conditions. Hence, Jeong K.S. *et al* in [25] considered two control approaches to increase hybrid system efficiency. The hybrid system efficiency was reduced when the controller maintained the battery SoC at the optimum level. On the other hand, the hybrid system efficiency was increased by allowing the battery to supply more energy without considering SoC. The Rule based system consisted of five rules to determine the DC/DC converter power states. The introduced fuzzy logic controller in [25] optimized the operating FC system efficiency while maintaining the battery SoC at reasonable level. However, in this analysis, the fuzzy rules did not represent all the possible power states in the hybrid system. For an example, during the high load power, the DC/DC converter operated in high power mode even battery SoC was high.

Eren Y. *et al* developed wavelet and fuzzy logic based supervisory controller for a hybrid electric system in [26]. The hybrid electric system was consisted with an ultra capacitor as a secondary power source. Even though, the hybrid electric configuration differs from the fuel cell and battery hybrid system, the proposed control architecture has a potential to be applied for the fuel cell and the battery hybrid electric system. The proposed power management architecture decomposed the load power demand into two referenced signals by using the Wavelet decomposition theory. High frequency signal was used for the ultra-capacitor and the low frequency power signal was used as the referenced signal for fuel cell power. In additional to the referenced power, the fuzzy logic controller received feedback from the fuel cell current and the capacitor state of charge. The fuzzy outputs were the fuel cell power and the compressor voltage. This methodology shows that the fuel cell system was isolated from the transient power and operated at efficient power region. Eren Y. *et al* revealed that the hybrid system transient response was improved and at the same time, the fuel cell oxygen starvation was prevented by the fuel cell controller.

Zandi, M. *et al* [27] introduced a flatness control technique (FCT) for the hybrid system energy management. The FCT was combined with a fuzzy logic controller and formed a new energy management concept for the hybrid system power sharing. The FCT controlled the power flow between the fuel cell system and the storage devices and the fuzzy logic controller decided the operating power mode of the hybrid system. In this hybrid configuration, the fuel cell was connected to a DC bus capacitor and the

2. LITERATURE REVIEW

supercapacitor bank also connected to the same DC bus capacitor through a bidirectional converter. The second DC bus capacitor connected the battery and the first DC bus capacitor. The DC bus capacitors formed a flat system for control variables and feedbacks. In the flat system control architecture, the energy equations of the capacitors were differentiated and obtained the governing power flow equations for DC/DC converters. In this hybrid configuration, the fuel cell system was isolated from the load power and the DC bus capacitors responded to the step load changes. Hence the fuel cell system was operated in a constant voltage even at high step load changes.

Thounthong P. *et al* [28] proposed a hybrid system control strategy to prevent the fuel cell oxygen starvation. The fuel cell system considered as an energy supplying device for the battery. The battery was directly connected to the DC load and the fuel cell system was connected through a step-up converter. In this configuration, the fuel cell system was isolated from the load and operated as a power generator to charge the battery. The control loops were defined to control the fuel cell current and the battery SoC. As the main advantage of this configuration, the effects of the load current changes to the FC system were lower due to the power source isolation. Results showed that the transient response to the load current changes has improved in comparison to the fuel cell only application. However, this kind of hybrid configuration shows poor performances in long range application due to the battery charging constraint. Normally the battery charging current is lower than the load current and the battery charging time is last long at least 3 hours in automobile applications. Therefore, the battery charge is gradually decreased with the operational time period.

Thounthong P. *et al* developed a hybrid electric system by combining the PEM fuel cell with the battery and the supercapacitor bank in [29]. A unidirectional converter was connected to the PEM fuel cell system and the battery and the supercapacitor were connected through bidirectional converters. The current control loops were developed to control current flow of the power sources. The supercapacitor's benefits such as high power density and fast dynamic response improved the hybrid system performances. The supercapacitor bank reacted to the sudden load current changes as a transient power device and prevented battery from sudden charging and discharging events. The energy management strategies developed by Thounthong P. *et al* [29] were based on the power sources dynamic characteristics. The PEM fuel cell system which showed the slowest dynamic response operated as the power generator for the battery.

During the constant load power, the battery and the supercapacitor supplied the load power and at the same time the fuel system charges battery. On the other hand, the supercapacitor bank and the battery absorbed the regenerative braking power at different rates. Thounthong P. *et al* defined rule based for the hybrid system optimum power sharing. This hybrid configuration showed the improved results in terms of dynamic response to the load power changes. However, Thounthong P. *et al* ignored the effects of the additional weight accumulated by the supercapacitor bank and the power converter to the overall system. In automobile applications, the specific power of the power plant is a major design consideration and additional weights reduce the vehicle dynamic performances.

Kim M.J. *et al* [30] introduced stochastic dynamic programming (SDP) technique to control the fuel cell hybrid electric vehicle which developed by DaimlerChrysler in 2005. Initially, the SDP technique with Markov chain was developed to control the parallel hybrid electric vehicle in [31]. The same control technique was used for the fuel cell and battery powered hybrid electric configuration and verified through the real time implementation. The SDP optimization technique considered to minimize the hydrogen consumption by controlling the fuel cell current while measuring the battery SoC, wheel speed and the power demand. In this optimal control technique, the battery was allowed to supply the transient power and the fuel cell operated at an efficient region contributing more power to the propulsion. The results have shown that the vehicle miles per gallon gasoline equivalent was doubled in comparison to the similar gasoline powered vehicle. This model predictive power management system has successfully minimized the hydrogen usage while the fuel cell operated as the main power sources. However, in this hybrid architecture, the battery was directly connected to the DC bus and the hybrid system power flow was not control by the power converters. Therefore, the battery energy utilization and the battery life time analysis might be compromised with the final result outcomes.

Lin C. *et al* [32] proposed another SDP control architecture with the PEM fuel cell system model developed by [33]. In [32], the PEM fuel cell system characteristics were deeply analyzed and developed a reduced order fuel cell system model which had only two states by considering the nine state original model developed by [33]. Then, the reduced order fuel cell system was integrated into a hybrid electric vehicle model which had a DC/DC converter connected to the fuel cell system and the Li-Ion battery was

2. LITERATURE REVIEW

directly connected to the DC bus. A current control unit was introduced to the DC/DC converter regulation. In the power management strategy, a control loop was developed to determine the fuel cell current based on the load power demand. The vehicle power demand was described by a Markov chain and considered as a state variable for the SDP. In addition to the power demand, the battery state of charge and the wheel speed were defined as the state variable for the SDP. The optimization process consisted with a hydrogen consumption cost function that was minimized by controlling the fuel cell current. The optimal fuel cell current obtained from the SDP was the control command for the DC/DC converter. The SDP model was compared with the rule based system and observed 8% less hydrogen consumption for the same model. In addition, the SDP model FC system efficiency had increased 5% compared to the rule based system model due to the changes in the fuel cell operating point. Results comparison shows significant improvements in the SDP control architecture. However, the improved percentages might be varied with the rule based system conditions which are associated with human linguistic rules. Therefore, a referenced model with a rule base output is not commonly used in the performance comparison due to the flexibility of the rule changes.

Jin K. *et al* developed a power management system for the fuel cell and the battery powered hybrid configuration in [34]. Regulated hybrid power architecture was introduced with a unidirectional power converter (UDC) for fuel cell system and a bidirectional power converter (BDC) for the battery. The BDC was the main power flow controller and regulated with current and voltage control loops. Similarly, the UDC also regulated with current and voltage loops and activated the control loop at appropriate stages. The hybrid system operating condition was divided into nine regions and switched in between each region based on the battery and the DC bus voltages. Jin K. *et al* in [35] improved the power management architecture by introducing a tree level buck/boost bidirectional converter. The development stages of the buck/boost BDC has published in [36]. The hybrid system design considerations were deeply analyzed and included all the possible hybrid system power status in to the power management system. Jin K. *et al* successfully addressed the hybrid system power flow control by allowing the BDC to control the battery charging and discharging stages. The results showed that the hybrid system efficiency has increased significantly . In addition to that, the hy-

brid system dynamic characteristics were improved as the results of the power flow controllability.

2.5 Intelligent Power Management

Intelligent power management (IPM) is a modern power handling concept that has developed several researchers for many applications. In literature, the intelligent power management applications are ranged from the computer processors power management, electric vehicle power management to large scale grid system power management. In the electric vehicle domain, the intelligent power management techniques have been used in the sectors such as propulsion system power management and battery charging systems. In the electric vehicle, the power management and distribution system (PMDS) allows the efficient power sharing between the power sources. By including intelligent power management algorithm into the PMDS, the optimized performances can be achieved from the the propulsion system. The power management algorithm is developed based on the power sources capacities, operational characteristics and by considering the type of the power sources such as fuel cell, battery and supercapacitors.

The intelligent power management can be represented as the combination of the advanced algorithms and their applications in real time environment. In terms of the algorithms, state machines, neural network system, fuzzy logic controllers and adaptive neuro fuzzy controllers are mainly implemented in the power management and the distribution box.

Hatti M. *et al* in [37] developed an artificial neural network to control the DC/DC converter connected to fuel cell system in multiple power source hybrid system. The voltage and current controller generate the desired duty cycle for the converter. The neural network controller tracked the maximum power point of the photovoltaic (PV) array and changed the operational power of the fuel cell based on the PV maximum power point. As the main power source, the PV array generated power for load and supplied the additional power to electrolyzer to produce the hydrogen gas. When the load demand is high, the fuel cell started to supply the balance of the power. The power distribution was decided based on the power demand and the maximum power point

2. LITERATURE REVIEW

of the PV array. The fuel cell power was controlled by changing the duty cycle of the DC/DC converter. The neural network power management strategy was more beneficial for the dynamics system which required power point tracking.

Chakraborty S. *et al* in [38] developed an intelligent power management system with a predictive module for a grid connection. The predictive module consisted of fuzzy and ARTMAP which could perform supervised learning in response to the input vectors. This fuzzy-ARTMAP could forecast the future energy demand based on the previous data. A state machine was developed to select the optimization schemes which consisted of the cost minimization and the energy optimization algorithms. The online module was included with the feedback loops to identify the power balance changes.

In the most of the power management applications, the load sharing sequences are implemented by using the state machines or supervisory controller and for the optimization purposes, the researchers used the control algorithms such as machine learning, neural network or fuzzy systems. In the intelligent power management perspective, the hybrid system power sharing strategy and the power sources performance optimization methodologies are combined and form a novel power management system. In the intelligent power management system, the power management sequences are developed to decide the power splitting sequences and the controllers optimize the hybrid system performances based on the power splitting sequences.

There are some applications related to the intelligent power management system developed by the researchers focused on the optimization of the operational parameters such as fuel cell temperature and fuel cell current.

2.5.1 Adaptive Neuro Fuzzy Control

Adaptive neuro fuzzy inference system (ANFIS) is an adaptive control methodology which can learn from the feedback and trains the control output to achieve the desired target. The ANFIS theory was gradually developed and the pioneers of this concept were [39], [40] and [41]. As the major advantages of the ANFIS based control architecture which was developed by [39], [40] and [41], the adaptive controller can adapt to the nonlinear system and can define approximated initial conditions for each state transition. The adaptive neuro fuzzy concept is widely used in the electric vehicle power management widely used in

Hajizadeh A. *et al* developed a three layered control structure in [42] to optimize the hybrid system power sharing. The first layer consisted with supervisory control architecture to determine every possible operating modes of the hybrid system. The second layer used the fuzzy logic control strategy to make the decisions associated with power management and the third layer regulates the set points of the each local controller of the fuel cell, the battery and the DC/DC converter. The supervisory controller consisted of the three operating modes which were called battery, hybrid and recharge. The fuzzy logic controller made the decisions to operate the fuel cell system in different power point to optimize the hybrid system power sharing. An intelligent power management strategy implemented through neuro-fuzzy controller which adapted the local controller set points to desired values. The IPM strategy described in [42] showed greater performances in terms of the power management. However, the simulation results did not include any adaptation process done by the neuro-fuzzy controller to the local controllers.

Another Adaptive Neuro-Fuzzy Inference System (ANFIS) introduced by [43] to control the temperature of the PEMFC system. This ANFIS controller decided the fuel and air flow rates and hence controlled the FC stack temperature. The ANFIS controller operated as a nonlinear system identifier which has described in [41]. The learning and training processes of the ANFIS controller controlled the air flow rate of the fuel cell system to achieve the desired temperature. In order to maintain the desired temperature, the air flow rate was increased when the temperature exceeded the desired value and the flow rate was decreased when the actual temperature was lower than the desired value. The error back propagation algorithm and least square methods adapted the output variables continuously according to inputs variables changes. The same authors, Sun T. *et al* introduced the Levenberg-Marquardt algorithm to the ANFIS controller due to slow speed of the back propagation training algorithm [44].

2.6 Fuel Cells

Fuel cell is an energy converting device that converts chemical energy into electrical energy. The fuel cell has an efficient energy conservation process compared to the other energy converting devices such as gasoline engines and solar panels. As the results

2. LITERATURE REVIEW

of the technological development, a hydrogen fuel cell stack shows 50-60% energy efficiency at steady-state operation [22]. The fuel cell reactants, temperature, humidity and water level should maintain at appropriate levels in order to operate in efficient region. The fuel cells have developed as a system level approach by combining the fuel cell stack with the subsystems such as temperature control subsystem, humidity control subsystem and water management subsystem to achieve greater performances. The fuel cell subsystems which are called balance of plant (BoP) are mainly consisted with a compressor, a compressor motor, a power conditioning unit, a cooling pump, a humidifier and pressure regulators. The FC system efficiency is reduced between 40% to 50% as the results of the power consumed by the fuel cell BoP [45]. The hydrogen powered PEM fuel cell stack and the subsystems are shown in figure (2.2).

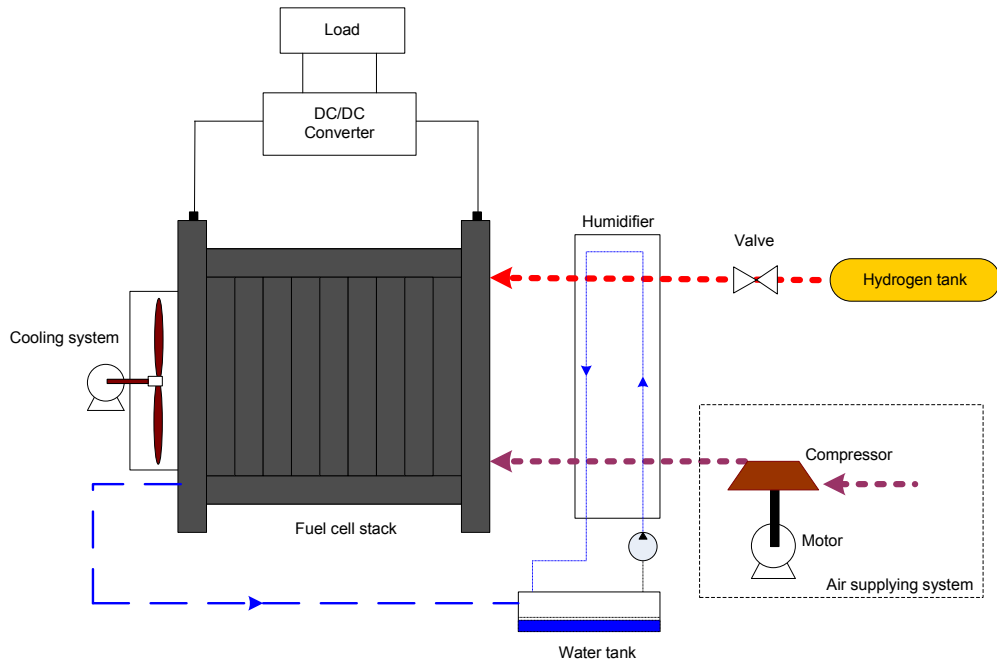


Figure 2.2: Fuel cell stack and subsystems

The PEM fuel cell is mainly consisted of a polymer electrolyte membrane, electrodes and a current collector. The numbers of cells are stacked together and form a fuel cell stack with higher power density. The air supplying system which is consisted of a motor and a compressor controls the inlet airflow rate and pressure of the fuel cell stack. In most applications, the hydrogen gas is stored inside a pressurized gas cylinder and

the hydrogen gas flow is controlled by the pressure regulator . The humidifier controls the fuel cell stack humidity by injecting vapors into the airflow. The cooling system of the fuel cell controls the cell temperature by circulating the cooling medium. The method of cooling such as air cooling or water cooling is depended on the fuel cell power capacity. The fuel cell systems which have low power capacities are cooled by using the air as the cooling medium. The power conditioning unit which is consisted of a DC/DC boost converter regulates the fuel cell voltage.

The FC power output is mainly depended on the cell temperature, the stack humidity, reactant flow rate and the reactants pressures [46]. The changes in these parameters influence the fuel cell voltage losses such as activation overvoltage, concentration losses and voltage drop caused by the FC internal resistance. The FC parameters are interrelated to the each other and changes in one parameter affect to another parameter. In order to increase the fuel cell system efficiency, the fuel cell losses should be minimized and a proper fuel cell controller should be implemented. The fuel cell stack voltage losses and effects of the cell temperature, reactants pressures will be discussed in chapter (3).

2.6.1 Fuel Cell History

The British scientist, Sir William Grove invented the fuel cell in 1839 [47]. He found that the electricity is generated as the result of the hydrogen and oxygen gases reaction inside the electrolyte [47]. In 1893, Wilhelm Ostwalt a German chemist and a founder of the field of physical chemistry, investigated the fuel cell reactions and the related theories were published in [4]. The first hydrogen and oxygen powered fuel cell was developed by Dr. Fransis Thomas Bacon (1904-1992) [4]. In addition to that, Dr. Bacon developed an Alkaline fuel cell in 1959 and his Alkaline fuel cell concept was used in Apollo spacecraft program since 1961 [4]. Allis Chalmers developed a fuel cell powered tractor in 1959 as the world first fuel cell vehicle [48]. Table 2.1 shows the key milestones in fuel cell history [4].

In early 1960s, the United States Federal Government invested in the fuel cell researches for the military and aerospace applications and aimed to validate the high efficiency and durable energy converting device that could replace the internal combustion engines [47]. However, this program was unsuccessful as the results of the technological

2. LITERATURE REVIEW

difficulties associated with the fuel cell development such as the cooling system of the Alkaline fuel cell. After invention of the Alkaline fuel cell (AFC) by Dr. Francis Thomas Bacon who worked at Cambridge university in 1940 to 1960, the National Aeronautics and Space Administration (NASA) of the U.S. encouraged the scientists to develop the AFCs for Apollo space missions launched in 1969. However, research interest in the fuel cell system development declined in early 1970s due to the technical difficulties such as volume constraint, control problems associated with water management and thermal management and high cost involved in the fuel cell system components. In the early 1990, again fuel cell based researches increased tremendously after the invention of direct Methanol fuel cells. The fuel cell vehicles were appeared as an environment friendly transport solution to replace the fossil-fueled driven vehicles. In 2003, the U.S. energy department launched a fuel cell learning demonstration programme for 12 years period which will be ended up in 2015 with a sustainable energy solution for the automobile applications [49]. Similarly, European commission started programme called 'European Hydrogen and Fuel Cell Technology Platform' to expand the fuel cell based energy solution for transport and stationary power applications since 2009 [50].

Mock P. and *et al* conducted techno-economic assessment in [51] about the fuel cells and their future trend based on the patent applications and the related scientific publications. The fuel cell related publications were increased from 200 per year in 1995 to more than 2000 per year in 2006 [51]. It has revealed that, after 1990s, most fuel cell publications were related to the PEM fuel cell applications. In terms of the patent applications, the alkaline fuel cell related patent applications percentage was the highest during the 1960s and 1970s as the result of the aerospace program. After mid 1990s, PEM fuel cell related patent applications were gradually increased and exceeded the 0.2% applications among the total patent applications in early 2000s [51]. The fuel cells have succeeded in laboratory experiments and in the large scale fuel cell projects such as Apollo spacecraft program and stationary power stations. However, so far the fuel cells have failed as a viable energy converter in commercial applications such as automobile industry and portable power devices due to the higher production cost and the technological difficulties such as hydrogen storage and transport, refuelling and safety issues.

Table 2.1: Key milestones of the fuel cell history (Extracted from I. Eduardo [4])

Year	Description
1800	British scientists William Nicholos and Anthony Carlisle had described the electrolysis of water
1838	Willium Robert Grove created the first fuel cell called 'gas battery'
1889	Ludwig Mond and Carl Langer increased the FC current density
1893	Friedrich Wilhem Ostwald formulated fuel cell theories
1930	Emil Baur and H. Peris experimented the high temperature Solid Oxide electrolite
1939	Francis Thomas Bacon started to develop Alkaline Fuel cells
1958	G.H.J. Borsers and J.A. Keteleer began to build a Moltan Carbonate fuel cells
1960	Thomas Grubb and J.A Keteleer developed the PEM fuel cell
1961	G.V. Elmore and H.A. Tanner experimented on Phosphoric acid fuel cells
1962	Apollo spacecraft mission used the Alkaline fuel cells
1990	NASA developed the direct methanol fuel cells

2.6.2 Fuel Cell Types

Fuel cells are categorized according to the type of the electrolyte used. Direct methanol fuel cells (DMFC), Alkaline fuel cell(AFC), Proton Exchange Membrane fuel cell (PEMFC), Phosphoric Acid fuel cell(PAFC), Molten carbonate fuel cell (MCFC) and Solid Oxide fuel cell (SOFC) are the main types of fuel cells used in industrial and automobile applications. Figure 2.3 shows the fuel cells range of applications and their advantages [2].

Figure 2.3 shows the DMFCs are commercially used in small portable applications. The AFC are mostly found in medium size applications such as small vehicles, boats and domestic power supplies. The PEMFC has wide range applications starting from 1W small portable applications to medium size vehicles and 100kW stationary power applications. The PAFCs are mostly installed in stationary power applications such as hospitals, military bases etc [2]. The SOFCs are used in large scale stationary power plant and heavy vehicle applications. The MCFC systems are large scale power plants and generate power for Distribute Generation (DG) systems at higher temperatures. J. Larminie *et al* [2] explained the major type of fuel cell systems and their advantages and disadvantages.

- Direct methanol fuel cells (DMFC)

2. LITERATURE REVIEW

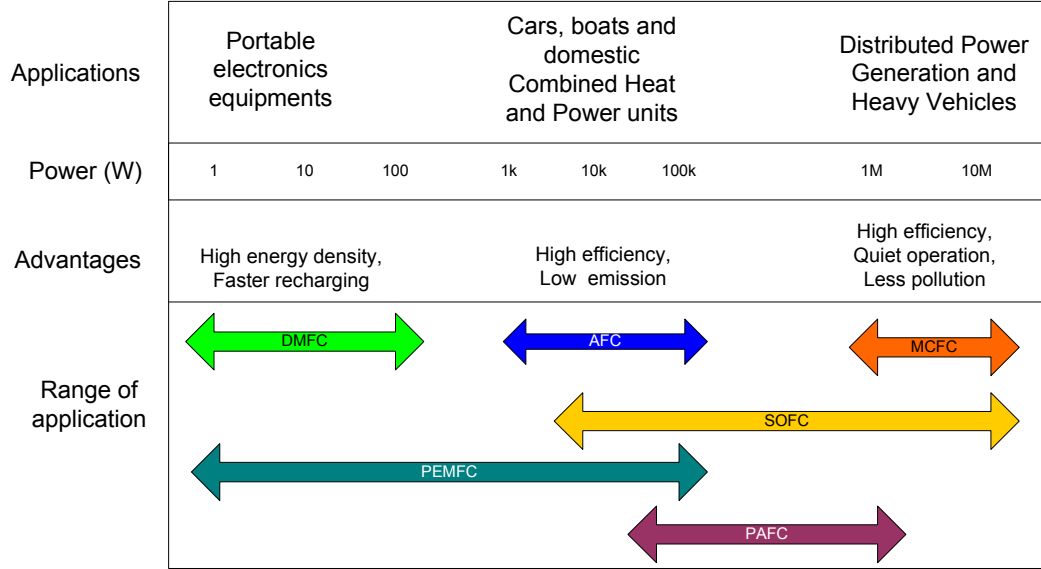
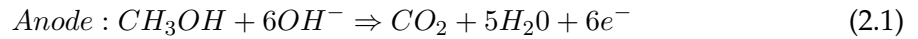
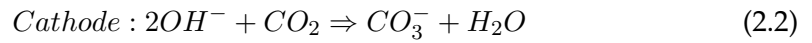


Figure 2.3: Fuel cell systems range of applications
(Reproduced from the J. Larminie et al) [2]

In the DMFC systems, methanol fuel is directly supplied to the fuel cell stack without hydrogen reforming. The DMFC's anode and cathode reactions are shown in equations (2.1) and (2.2) [2]. At the anode side, the methanol (CH_3OH) and alkaline OH^- ions from the electrolyte (KOH/ NaOH) are reacted and form CO_2 and H_2O . In the cathode side, CO_2 is reacted with OH^- ions and produced CO_3^- ions.

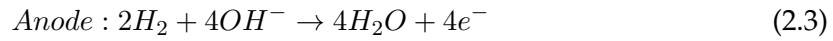
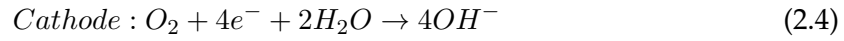


The DMFC power density is very low due to slow reaction rate. The DMFC's alkalinity is gradually reduced due to the formation of CO_3^- by combining of the OH^- ions and CO_2 gas. The DMFCs are important in the applications where hydrogen could not supply directly into the FC stack. The advantages of the DMFCs are the high methanol storage efficiency compared to the hydrogen storage and the methanol as a cheap fuel available in market [2]. The DMFCs are suitable for the small scale power applications such as portable power generators due to the low power density and high energy den-

sity of the fuel cell.

- Alkaline fuel cells(AFC)

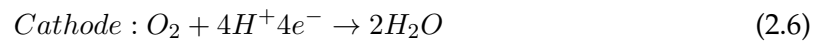
The AFC has a simple chemical reaction that releases the electrons at the anode and protons transfer to the cathode through the electrolyte which has liquid OH^- ions. The AFC anode and the cathode reactions are shown in equation 2.3 and 2.4 [2].



The AFC electrolyte can be potassium hydroxide (KOH) or sodium hydroxide (NaOH). The OH^- ions are combined with the hydrogen and form H_2O while releasing the electrons. The AFC has advantages such as low production cost which can be achieved by using Nickel catalyst and the simplicity of the fuel cell reaction. The main disadvantage of the AFC is the liquid electrolyte pump which circulates the electrolyte throughout the fuel cell stack consumes additional power from the fuel cell. Hence, the AFC net power output is lower than the theoretical value. In addition to that, the pure hydrogen gas should supply to the fuel cell. CO_2 gas should remove from the air before it enters into the fuel cell stack. Otherwise OH^- ions react with CO_2 gas and form K_2CO_3 and at the same time OH^- concentration is gradually decreased. These carbonate ions reduce the electricity conductivity and increase the activation losses [2].

- Proton Exchange Membrane fuel cells (PEMFC)

In PEM fuel cell systems, a solid polymer membrane is used as the electrolyte and platinum catalysts is used to accelerate the reaction process. The PEM fuel cell chemical reactions at the anode and the cathode are shown in equations (2.5) and (2.5) [2].

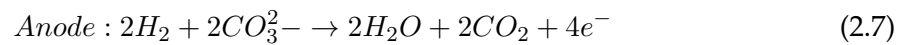
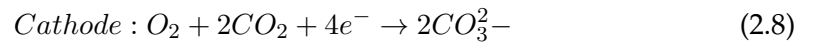


2. LITERATURE REVIEW

Hydrogen and oxygen gases react at the anode and the cathode respectively and generate the electricity. The hydrogen and oxygen fuel cell reaction produces the water and heat. The main advantages of the PEMFC system are the low temperature start up process and solid state energy transform without a liquid electrolyte [2]. In early 1960s, General Electric developed the first PEM fuel cell system [52]. The PEM fuel cell technology was used in NASA Gemini space project to supply the electric power needs for the shuttle and a source for drinking water [52]. In early 1990s, *Bollard Power system* developed the PEMFC stack with high current density per cell area and decreased the amount of platinum catalyst used. Roger Billings who is an inventor, developed the world first PEM fuel cell powered vehicle in 1991 [53]. Later on, the PEM fuel cell system has dominated as the most successful fuel cell solution for automobile applications. Mock P. *et al* predicted that the current PEMFCs technological development still in rapid growing rate and will be matured in year 2015 [51].

- Molten Carbonate fuel cells (MCFC)

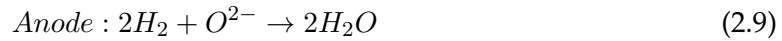
The MCFC's electrolyte is a molten carbonate mixture that conducts the CO_3^{2-} ions from cathode to anode. In the MCFCs, the H_2 gas is supplied to the anode and the O_2 and the CO_2 gases are fed into the cathode. The anode and the cathode reactions are shown in equations (2.7) and (2.8) [2].



An external CO_2 recycling processes is necessary in the MCFC system to transfer the CO_2 from the anode to the cathode. Due to the complexity of the MCFC systems, the most MCFCs are used in stationary power applications [2]. In the most MCFCs, a Nickel anode and a Nickel oxide cathode are used to accelerate the fuel cell reactions. The operating temperature of the MCFC is varied from $600^{\circ}C$ to $1000^{\circ}C$ [2]. The MCFC system start up time takes 14 hrs or more [2].

- Solid Oxide fuel cell (SOFC)

The SOFCs are operated at high temperatures between $800^{\circ}C$ and $1100^{\circ}C$. The solid electrolyte which is made by a ceramic material *Zirconia* conducts the oxygen ions at high temperature. The hydrogen gas or Carbon Monoxide (CO) gas can be used as the anode reactant. The SOFC's anode and cathode reactions are shown in equation 2.9 and 2.10 [2].



The SOFC's current density is high compared to the other types of fuel cells. Therefore, the SOFCs are suitable for large scale stationary power plants. The (CO_2) recycling process is not required for the SOFC system. The main disadvantage of the SOFC system is the high operating temperature compared to the other types of fuel cell systems [2].

2.6.3 PEM Fuel Cell Development

The development in the PEM fuel cell technology can be analyzed in different aspects such as stack power, power density, platinum loading, vehicle performances and hydrogen storage. *Ballard power system Inc* which is the large scale PEMFC system manufacturing company introduced a 110kW PEMFC system for automobiles application in late 1990s. In 1960s, the volumetric power density of the PEM fuel cell used in NASA Gemini project was $20Wl^{-1}$ [51]. In between 1980s and 1990s, the Ballard power systems improved the volumetric power density of the PEM fuel cell up to $1300Wl^{-1}$ [51]. Honda Group claimed $1900Wl^{-1}$ volumetric power density in 2010. The gravimetric power density of the PEMFC system has risen from $15Wkg^{-1}$ in Gemini project to $1000Wkg^{-1}$ in the latest Ballard power system Inc. The United States, Department of Energy (DOE) predicted $2000Wkg^{-1}$ gravimetric power density in year 2010 [49]. Electrodes platinum loading is the major influencing factor for cost of the PEMFC system. The cost of the Platinum loading is accounted 80% of total production cost [51]. According to the DOE data, the amount of platinum used for the electrodes has decreased from $28mg(cm^2)^{-1}$ in Gemini project to $0.7mg(cm^2)^{-1}$ in the current PEMFC systems [49]. The cost analysis of the mass production of the PEM fuel cell systems shows that

2. LITERATURE REVIEW

the price variation can be expected from 1300\$/kW per one system to 35 – 83\$/kW per one million system. In terms of vehicle performances, the fuel cell vehicle developed by Daimler (Necar-4) showed 50% efficiency in 1999 and F-Cell car showed almost 60% efficiency in 2001 [51]. The PEM fuel cell vehicle tested in New European Driving Cycle (NEDC) reached 45-50 % efficiency and the diesel engine tested in same driving cycle reached only 15-20% efficiency [51]. The PEM fuel cell powered vehicles tank to wheel efficiencies have increased dramatically compared to the gasoline engines driven vehicles. The PEMFC vehicle's performances such as maximum speed, vehicle efficiency, driving range and cold start-up have reached to the desired levels to compete with the IC engines [51]. However, the hydrogen storage efficiency and the power to weight ratio are the main issues that need to overcome.

2.7 PEMFC System Control

The control of the PEMFC system performances is important in order to achieve optimum performances from the electric propulsion. Three main control approaches can be identified based on geometrical variables, operational variables and performances variables. The geometric parameters decide the size of the fuel cell system, reactants flow paths and electrode thickness etc. The main operational variables are the fuel cell humidity, reactant pressures, flow rates of reactants and temperature of the fuel cell system. The performance variables are the fuel cell system power output, efficiency, transient response and fuel cell current. M. Grujicic *et al* introduced the PEM fuel cell geometrical design parameters optimization technique in [54]. The PEM fuel cell performances were optimized by changing the geometrical parameters such as electrodes and membrane thickness. The polarization curve of the geometrically optimized fuel cell increased compared to the reference polarization curve. The results showed that the fuel cell power density could be increased by changing the geometrical parameters. The optimum fuel cell design was not only depended on the cell geometry but also depended on the operational parameters such as inlet airflow rate and pressures [54]. However, M. Grujicic *et al* did not conducted a cost analysis for this optimization and only the performances were considered. The increase in electrodes sizes involve more Platinum catalyst usage which leads to high production cost.

Researches revealed that the PEM fuel cell system control parameters are interrelated to each other and changes in one parameter affect to the other parameters. In most research publications, the relationships between the performance parameters and the operational parameters were investigated and mostly ignored the effects from the geometrical parameters. The fuel cell current is the main performance variable and based on the fuel cell current, the operational variables such as cell temperature, membrane water content, air flow rate and the air pressures are controlled. The control of air supplying system, water management system and the cell temperature are vital to obtain the greater performances from the fuel cell in both transient and steady state scenarios. The PEMFC stack temperature is controlled by circulating the cooling fluid through the cooling plates and water content of the membrane controlled by humidifying the gas flows. The cell temperature should maintain at appropriate level to minimize the losses associated with cell voltage. The increase in the cell temperature vaporizes the accumulated water and hence water removal process can be accelerated. On the other hand, high temperature dries out the cell membrane and prevents the H^+ movements which causes the cell degradation [55]. In addition to that, the slow cell reactions rates are occurred at the low temperature of the cell [55]. The power consumed by the coolant power also reduced the overall cell efficiency [55]. Ahn J *et al* conducted a temperature control analysis in [55] by proposing a new thermal circuit with a radiator, a fan, a water tank and a coolant pump. Ahn J *et al* revealed that the fuel cell oxygen excess ratio is varied with the cell temperature [55]. When the cell temperature is increased, the oxygen excess ratio is reduced and the oxygen starvation might be occurred. However, the cell temperature dynamic is a slow process compared to the other variables such as oxygen excess ratio and membrane water content [56]. The effect of the temperature to the cell voltage will be discussed in chapter (3).

The fuel cell water management system maintains the membrane water content at the appropriate level and prevents the cell flooding. The cell is humidified by injecting the water into the reactant flow and accumulated water is removed by a purge valve connected to the fuel cell outlet manifold. Buchi F. *et al* revealed that 20% to 40% voltage losses could be occurred due to the lack of water management [57]. The sensitivity analysis conducted by [46] showed that the membrane water content effect was the most influencing factor to the fuel cell power output compared with other operational variable. The second most sensitive performance variable was the cell temperature and

2. LITERATURE REVIEW

lowest effect came from the reactants pressure variations. Springer T. E. *et al* conducted a model predict analysis in [58] which showed the relationship between the membrane water content and the membrane internal resistant variations. M. Whr *et al* mathematically modeled the diffusion layer, catalytic reaction layer and the kinetics of the polymer membrane and observed the effects of the operational variables to the cell potential [59]. M. Whr *et al* showed that the increase in the cell humidity minimized the cell potential losses hence improved the cell current density.

The parasitic power consumed by the cooling system is considerably lower than the power consumed by the air supplying system. The PEM fuel cell air supplying system dominates as the main parasitic power consumer from the hybrid power sources. Pischinger S. *et al* described the requirements of the air supply system in [60]. The effects of the air supplying system to the fuel cell system performances are extended in several aspects related to the cell humidity, air flow rate, air pressure and parasitic power. The control of the membrane water content is a major issue associated with air supplying system dynamics. The cell humidification process should control in order to prevent the cell drying [60]. In addition to that, the high air flow rate evaporates the membrane water. If the membrane water vaporization rate is higher than the rate of water produce by the reaction, the membrane starts to dry out and damages physically. The cell humidification, the control of the membrane water content and the control of air flow rate are interrelated processes and the detailed investigations have been conducted by the researchers. However, in most cases, the relationship between the fuel cell voltage and the air supplying system's parameters such as air flow rate and the air pressure are considered in the hybrid system analysis. The air supplying system consumes approximately 6% of the fuel cell power. Hence, the optimization of the fuel cell air supplying system shows greater effect to the fuel cell power than the other operational parameters optimizations. In most fuel cell control publications, the PEM fuel cell systems were mathematically modeled and introduced different control methodologies to the air supplying system to optimize the fuel cell performances.

J.T. Pukrushpan *et al* developed a successful mathematical model in [56] to represent the fuel cell characteristics. This fuel cell system mathematical representation was mainly focused on the control aspects of the air supplying system and the water management system. J.T. Pukrushpan *et al* analyzed the compressor motor characteristics, manifold-filling dynamics and humidity control and developed a fuel cell system which was

suitable for the control analysis. However, the fuel cell model developed in [56] ignored the cell temperature variation due to the slow transient effect and assumed that a separate controller controls the stack temperature. J.T. Pukrushpan *et al* mathematically modeled the air compressor, the PEM fuel cell stack, the supply manifold, an air cooler and the humidifier. In [56], the fuel cell stack polarization curves indicated that the cell voltage was increased by increasing the cell air pressure. The PEM fuel cell net power output was defined as the power different between the power generated by the fuel cell stack and the power consumed by the fuel cell system compressor motor. The simulation results of the [56] showed that the fuel cell system net power output could be increased up to the certain levels in different currents and beyond that peak points, the fuel cell net power output was decreased. In high load currents, the fuel cell compressor consumed more power than the power gained by increasing the air pressure and flow rate. Hence, the fuel cell net power was gradually decreased with the increased in pressure ratio. The detailed description about the fuel cell power and air supplying system dynamics will be described in chapter (3).

In [61], J.T. Pukrushpan *et al* formed a nonlinear feedforward and linear feedback controller to regulate the oxygen excess ratio with the fuel cell current changes. The feedback controller showed more robustness to the air flow during the step load current changes. M. Grujicic *et al* in [62] developed a control strategy for the transient behaviour of the PEM fuel cell system. The cathode oxygen level was successfully maintained by controlling the compressor motor voltage through a feedback controller. The same analysis were carried out by [63] and suggested the necessity of a secondary power source and a power management architecture. In [63], the fuel cell system which was represented by nine state space equations normalized at maximum net power point. The dynamic model included the oxygen, nitrogen and water mass flow rates of the cathode and the anode hydrogen and water flow rates. The supply manifold pressure, the compressor speed and the return manifold pressure were included to the fuel cell model. M. Grujicic *et al* in [63] developed an Observer design to control the oxygen excess ratio. The controller input variable was the compressor motor voltage and output was the oxygen excess ratio. The Observer feedback controller based results were compared with the feedforward controller and found that the feedforward controller rise and settling times were long and involved in transient overshoots [63]. The observer-based integral feedback controller reduced the rise and the settling time for the oxygen excess

2. LITERATURE REVIEW

ratio during the transient step current changes [63]. The Observer based feedback controller showed relatively high robustness to the step current changes and maintained the optimal level of the oxygen ratio. However, in the Observer based feedback controller, the transient response time to the load current changes was still high and the achieved small reduction of the transient response time over the feedforward controller was not sufficient to supply the continues power without abnormal changes [64]. This implies that the requirement of the power management system with a secondary power source for fuel cell propulsion applications.

The PEM fuel cell and the battery hybrid power architecture requires an advanced power management system to share the load power between each power source and at the same time the fuel cell system performances should be optimized. The hybrid system power management and the fuel cell control can be interrelated each other by introducing a proper control architecture.

PEM Fuel Cell Systems and Cathode Dynamics

The fuel cell technology has developed dramatically over the past decades as the results of the technological advances. The fuel cells are attractive to the most propulsion applications as an alternative energy solution which has high energy density and high operational efficiency. In addition to that, the hydrogen fuel cell emerges as an environmental friendly energy converting device which produces zero emissions during the propulsion. The fuel cell system current and the operational variables such as temperature, humidity, air flow rate and air pressure are interrelated to each other. Hence changes in the fuel cell current affect to the fuel cell performances. It is necessary to maintain the operating conditions of the fuel cell at appropriate levels in order to achieve an efficient energy conversation. As described in literature review, the fuel cell system needs to operate in the optimum power region by controlling the performance variables and the operational variables.

In the first part of this chapter, the basic theories of the PEM fuel cell are presented. A PEM fuel cell system is mathematically modelled in Simulink by considering the voltage losses associated with the cell temperature and the reactants pressures. In the later part of this chapter, the relationship between the net power output of the fuel cell

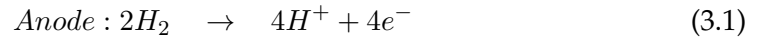
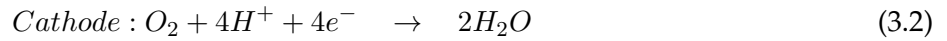
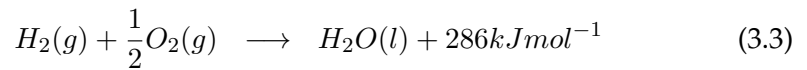
3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

and the control of the air supplying system is discussed. The optimized compressor power model is used as a referenced model for the adaptive controller which describes in chapter (6).

3.1 PEM Fuel Cells

The Polymer Electrolyte Membrane or Polymer Exchange Membrane which is known as PEM fuel cells are widely used in the automobile applications due to their compactness, solid structure and relatively low start up temperature. In addition, the PEMFC systems are populated in the electric vehicle industry as an efficient energy converting device compared to the other power devices such as IC engines and batteries. Nowadays, the PEMFC systems research momentum is turned to the aviation sector to develop fuel cell powered small scale aircrafts and the unmanned aerial vehicles [11].

For the PEM fuel cell system performance analysis, the basic hydrogen fuel cell reactions which are shown in (3.1) and (3.2) are considered. These reactions produce water and release heat and electrons [65]. The fuel cell reaction is similar to the formation of the liquid water by using the hydrogen and the oxygen gases (3.3) [65].



During the hydrogen fuel cell reaction, the anode side is fuelled with the hydrogen gas (H_2) and the anode electrode splits the H_2 gas into protons (H^+) and electrons ($-e$). The H^+ ions are combined with oxygen molecules (O_2) and the electrons ($-e$) and produce water (H_2O) molecules at the cathode. In order to complete the electrical circuit, the electrons are passed through the electric load and the protons are moved through the electrolyte.

For the PEM fuel cell, the anode and the cathode reactions are same as the basic fuel cell reactions described in (3.1) and (3.2). The PEM fuel cell electrodes are separated by the sulphonated solid polymer (SO_3^-) which only transfers H^+ from the anode side

to the cathode side. The advantages of the solid electrolyte membrane such as highly chemically resistant, mechanically strong and ability to form thin layers improve the PEM fuel cell system's volumetric efficiency.

The protons which are moved towards the cathode are combined with the oxygen and produce the water. As the result of the PEM fuel chemical reaction, heat is released from the cell and as the result of that the cell temperature increases gradually. For the constant operation of the fuel cell, the cell temperature, membrane water level and reactants flow rates and pressures are required to control by using the fuel cell controller. The fuel cell control system is divided into subsystems such as a water management system, an air management system and a temperature control system. The basic PEM fuel cell configuration is shown in (3.1). The cathode and the anode are separated by the membrane and the current collectors are placed to connect the electrical load to the fuel cell system.

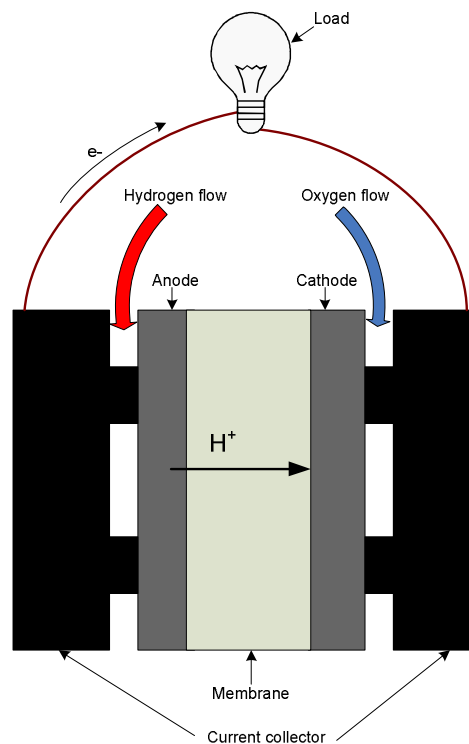


Figure 3.1: *PEM fuel cell structure*

3.2 Cell Voltage

The hydrogen fuel cell reaction creates a potential difference between the electrodes. The theoretical derivation proves that the fuel cell open circuit voltage is mainly depended on the reactants pressures and the cell temperature. In addition to that, the losses associated with the fuel cell reactions reduce the cell voltage below the theoretical value. The fuel cell operational losses which are known as the Concentration loss, Ohmic loss and Activation polarization loss are significant issues in the fuel cell control [6].

3.2.1 Open Circuit Voltage

In hydrogen fuel cells, the input energy is converted to the electricity and heat. The 'Gibbs free energy (ΔG)' which is the energy converted into the electricity can be expressed as the energy difference between the reaction enthalpy (ΔH) and the creation of the entropy (ΔS) [65],

$$\Delta G = \Delta H - T\Delta S \quad (3.4)$$

The equation (3.3) shows that the formation of the liquid water from the hydrogen gas at higher heating value releases energy $\Delta H = 286.02 \text{ kJmol}^{-1}$ [65]. Thermodynamics fundamentals have been derived that the entropy for the fuel cell reaction is $0.1632 \text{ kJmol}^{-1} \text{ K}^{-1}$ and the energy converts into the heat is 48.68 kJmol^{-1} at the standard temperature and pressure [65]. From the equation (3.4), the energy converted into the electricity is determined at the standard pressure and the temperature, ΔG is $237.34 \text{ kJmol}^{-1}$.

The electrical work (W_{el}) done by the fuel cell is denoted by the charge (q) times potential (E). The equation (3.1) shows that the one hydrogen molecule is used to produce one water molecule while two electrons flowing through external circuit. The electrical work done by the reaction is shown in (3.6) [65],

$$W_{el} = q \times E \quad (3.5)$$

$$W_{el} = 2 \times (-e) \times E \quad (3.6)$$

$-e$ is the electron charge and the E is the cell voltage. For the one mole of hydrogen, the total number of electrons movement is $2 \times N$. N is the Avogadro's number. By applying the Faraday's constant ($F = N \times e$) to the (3.6) the electrical work done by the one mole of hydrogen is,

$$W_{el} = -2FE \quad (3.7)$$

By assuming the reaction is reversible, the electrical work done can be represented in the Gibbs free energy formed.

$$\Delta G = W_{el} \quad (3.8)$$

$$\Delta G = -2FE \quad (3.9)$$

From (3.4) and (3.9), the theoretical open circuit cell voltage is shown in (3.11) [65],

$$E = -\frac{\Delta G}{2F} \quad (3.10)$$

$$E = -\frac{1}{2F}(\Delta H - T_{fc}\Delta S) \quad (3.11)$$

T_{fc} is the fuel cell temperature. The fuel cell theoretical open circuit voltage is obtained as $1.229V$ at the standard pressure and the temperature [65].

3.2.1.1 Pressure Effect

The effect of the reactants partial pressures to the Gibbs free energy formation has been formulated by German physical chemist Walther Nernst in 1920 [2]. The Nerst equation describes the effects of the reactants partial pressures to the cell potential at the different temperatures. For the fuel cell control, the cell power gained due to the pressure effect and the power consumed for gas pressurization are necessary to investigate. A possible disadvantage of the gas pressurization is the power consumed by the pressurization

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

process might be higher than the additional power produced by the FC stack in the same instant. Therefore, this compromising control scenario is addressed by analyzing the fuel cell fundamentals in details.

For the gaseous condition of the reactants, the Gibbs free energy formation is shown in (3.12) [65].

$$\Delta G = \Delta G_0 + R_u T \ln \left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \right) \quad (3.12)$$

ΔG_0 is the Gibbs free energy formation at standard pressure and the temperature. P_{H_2} , P_{O_2} and P_{H_2O} are partial pressures of the hydrogen, oxygen and water. R_u is the universal gas constant. If the water is in liquid state then the $P_{H_2O} = 1$. From (3.4) and (3.12), the open circuit voltage E can be expressed as [65],

$$E = -\frac{\Delta G_0}{2F} + \frac{R_u T_{fc}}{2F} \ln \left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \right) \quad (3.13)$$

By assuming the temperature remains in a constant value, the cell potential (E) variations with current densities in different oxygen partial pressures are plotted in figure (3.2). When the air pressure is increased, the cell voltage has risen gradually.

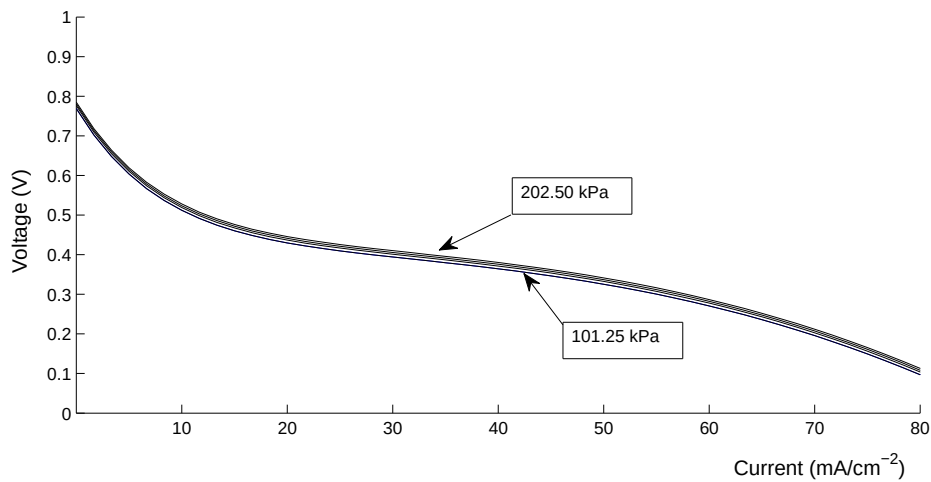


Figure 3.2: Effect of the air pressure

3.2.1.2 Temperature Effect

It has been emphasized that the cell temperature changes make a significant impact to the fuel cell electrochemical reaction. The equation (3.11) shows that the cell voltage is a function of the cell temperature. Both ΔH and ΔS are negative values and depended on the cell temperature [65]. Therefore the increase in the cell temperature reduces the cell voltage [65]. The relationship between the cell voltage and the temperature are shown in (3.14) [65].

$$E = -\left(\frac{\Delta H}{2F} - \frac{T_0 \Delta S_0}{2F}\right) - \left(\frac{T_{fc} \Delta S}{2F} - \frac{T_0 \Delta S_0}{2F}\right) \quad (3.14)$$

The entropy change of the cell reaction is considered as a constant value for any temperature [65]. By assuming that $\Delta S_0 = \Delta S$, the temperature and pressure effects to the cell open circuit voltage can be expanded as shown in (3.15) [65].

$$E = -\left(\frac{\Delta H}{2F} - \frac{T_0 \Delta S_0}{2F}\right) - \frac{\Delta S}{2F}(T_{fc} - T_0) + \frac{R_u T_{fc}}{2F} \ln\left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}}\right) \quad (3.15)$$

The values for the terms $\frac{\Delta H}{2F}$, $\frac{T_0 \Delta S_0}{2F}$, $\frac{\Delta S}{2F}(T_{fc} - T_0)$ and $\frac{R_u}{2F}$ are determined in (3.16), (3.17), (3.18) and (3.19).

$$\frac{\Delta H}{2F} = \frac{-286.02 \text{ kJ mol}^{-1}}{2 \times 96495 \text{ C/mol}} = -1.482 \quad (3.16)$$

$$\frac{T_0 \Delta S_0}{2F} = \frac{298.15 \text{ K} \times (-163.28 \text{ J mol}^{-1} \text{ K}^{-1})}{2 \times 96495 \text{ C/mol}} = -0.25225 \quad (3.17)$$

$$\frac{\Delta S}{2F}(T_{fc} - T_0) = \frac{-163.28 \text{ J mol}^{-1} \text{ K}^{-1}}{2 \times 96495 \text{ C/mol}}(T_{fc} - T_0) = 0.85 \times 10^{-3}(T_{fc} - T_0) \quad (3.18)$$

$$\begin{aligned} \frac{R_u T_{fc}}{2F} \ln\left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}}\right) &= \frac{8.314472 \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1} \text{ mol}^{-1} \times T_{fc}}{2 \times 96495 \text{ C/mol}} \ln\left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{1}\right) \\ &= 4.308 \times 10^{-5} T_{fc} \ln(P_{H_2} P_{O_2}^{\frac{1}{2}}) \end{aligned} \quad (3.19)$$

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

By substituting the equations (3.16), (3.17), (3.18) and (3.19) to the (3.15), the open circuit voltage for the one fuel cell stack can be expressed as shown in (3.20) [6].

$$E = 1.229 - 0.85 \times 10^{-3}(T_{fc} - 298.15) + 4.308 \times 10^{-5} T_{fc} \ln (P_{H_2})^{\frac{1}{2}} + \ln(P_{O_2}) \text{ Volts} \quad (3.20)$$

From the equations (3.4) to the (3.20), It can be proved that the open circuit voltage is a function of the cell temperature and the partial pressures of the hydrogen and the oxygen. However, when the fuel cell is connected to the external load, the cell voltage varies nonlinearly due to the losses caused by the electrochemical reactions and the cell internal resistance.

3.3 PEM Fuel Cell Polarization

The fuel cell losses such as activation loss, ohmic loss, internal current loss and concentration loss reduce the cell voltage considerably. Figure (3.5) shows the typical fuel cell polarization curve. At the low current densities, the cell voltage decreases dramatically as the results of activation loss [2]. After the $20mAcm^{-2}$, the cell voltage is reduced linearly in middle part of the curve due to the cell ohmic loss [65]. At high current densities starting from $60mAcm^{-2}$, the cell voltage is decreased by the reactants concentration loss [6]. These fuel cell irreversibility should minimize in order to improve the cell power capacity. The fuel cell losses are described in the following sections and developed the Simulink model based on the derivations.

3.3.1 Exchange Current Density

The net current of the reaction is the difference between the electrons generated and the electrons consumed. At the zero external current, the electrodes reactions are at equilibrium state which is considered the forward and the backward reactions happened simultaneously. During the cathode equilibrium state, the protons move from the membrane to the electrode and at the same rate the electrons move from electrode

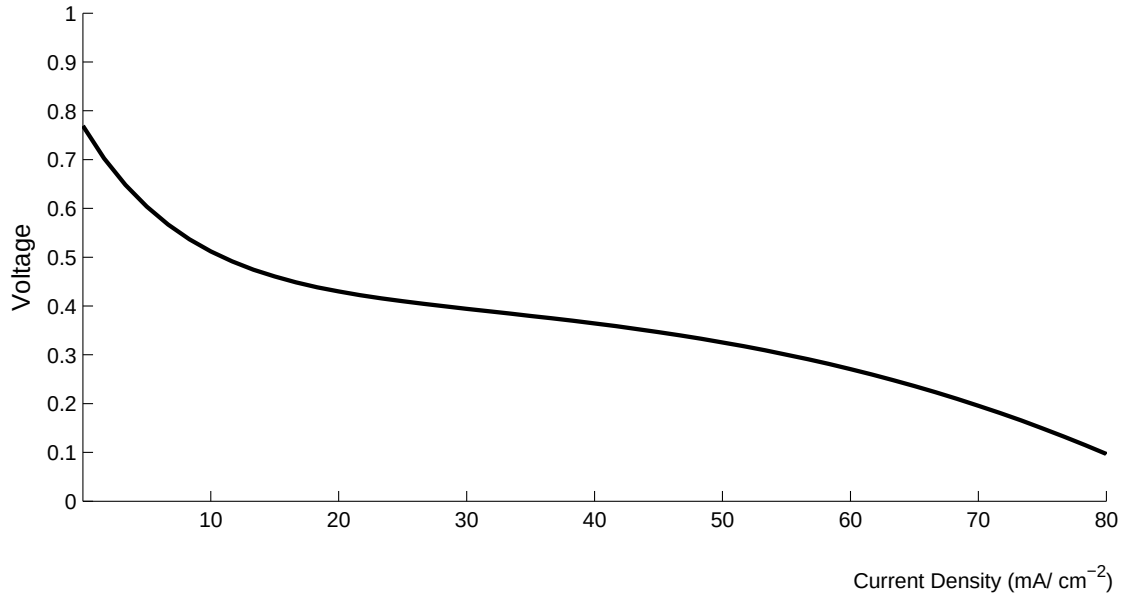


Figure 3.3: PEM fuel cell polarization curve

to the membrane. At the equilibrium state, the rate of these reaction is called 'exchange current density (i_0)' [65]. The exchange current density is depended on the concentration of the reactant, the cell temperature, catalyst loading and catalyst specific surface area [65]. If the exchange current density is high, the charge can easily move from the electrolyte to the catalyst surface area. The high i_0 reduces the energy barrier and accelerates the reaction process [65]. In the PEM fuel cells, the anode exchange current density $i_{0,a} = 10^{-4} \text{ A cm}^{-2}$ is higher than the cathode exchange current density $i_{0,c} = 10^{-9} \text{ A cm}^{-2}$ at standard pressure and temperature [65]. Therefore, the cathode dynamics are crucial factors in the fuel cell control.

In the literature, the effects of the cathode pressure variations to the exchange current density i_0 is derived as shown in (3.21) [65]. The equation (3.21) clearly shows that the increase in reactant partial pressure which is the oxygen partial pressure for the PEM fuel cell cathode increases the i_0 and hence consequently maximizes the cell current density.

$$i_0 = i_0^{ref} a_c L_c \left(\frac{P_r}{P_r^{ref}} \right)^\gamma \exp \left[- \frac{E_c}{R_u T} \left(1 - \frac{T}{T_{ref}} \right) \right] \quad (3.21)$$

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

i_0^{ref} = Reference exchange current density as standard pressure and temperature,

a_c = Catalyst specific area,

L_c = Catalyst loading

P_r = Reactant partial pressure

P_r^{ref} = Reference pressure

γ = Pressure coefficient

E_C = Activation energy, $66kJmol^{-1}$ for oxygen

R_u = Gas constant,

T = Temperature, K

T_{ref} = Reference temperature, 298.15K

3.3.2 Activation Loss

In the low current density region of the polarization curve shows sudden drop of the voltage. The activation loss occurs due to the slowness of the chemical reaction at electrode interface [2]. In 1905, the German chemist Julius Tafel observed the relationship of the electrochemical reaction with the current density and formulated equation (3.22) [65].

$$\Delta V_{act} = \frac{R_u T}{\alpha F} \ln \left(\frac{i}{i_0} \right) \quad (3.22)$$

$$\text{where } i > i_0 \quad (3.23)$$

α is the charge transfer coefficient which is determined empirically. The activation losses are appeared in both the anode and the cathode electrodes and have different rates. The hydrogen oxidation in the anode is faster than the reduction reaction in the cathode. Therefore, the cathode side activation loss causes the major impact to the cell voltage. Figure (3.4) shows the variation of the activation voltage losses with the cell current density.

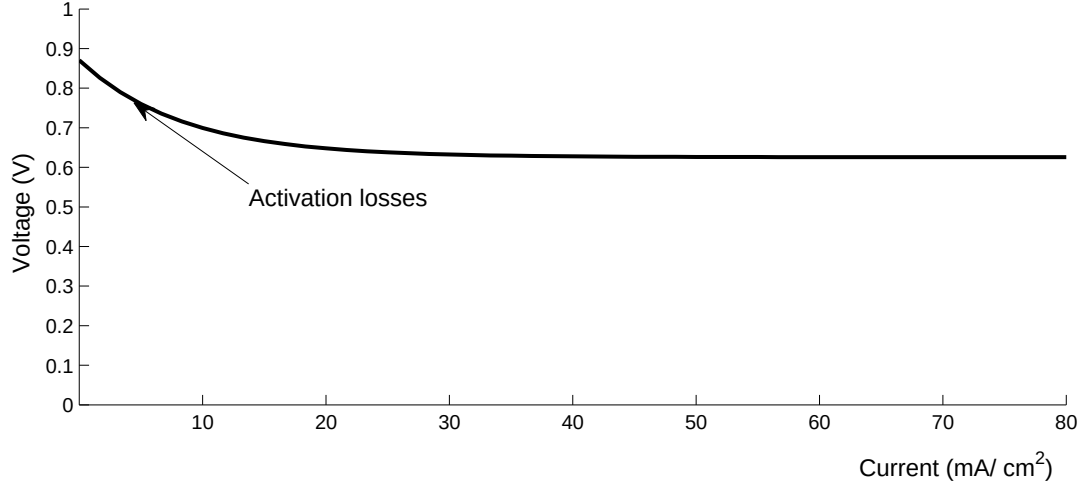


Figure 3.4: *Effect of the activation loss*

3.3.3 Ohmic Loss

Ohmic loss is the voltage drop by the fuel cell internal resistance. The total internal resistance is the summation of ionic and electronic resistances [65]. The membrane resistance is denoted as R_{mem} and the electronic resistance of the current collector is expressed as R_{elec} . The ohmic voltage drop is proportional to the fuel cell current i_{fc} as shown in equation (3.24) [65]. The ohmic loss is linearly varied with the current densities at the constant temperature.

$$\begin{aligned}\Delta V_{ohmic} &= i_{fc}(R_{mem} + R_{elec}) \\ \Delta V_{ohmic} &= i_{fc}R_{int}\end{aligned}\tag{3.24}$$

3.3.4 Concentration Loss

When the fuel cell current is increased, the electrochemical reactions rates are also increased. The concentration loss occurs at the electrodes due to the sudden reduction of the reactants. The high current density reduces the reactants concentration at catalyst surface sooner than the low current density. If the reactants are supplied at maximum

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

rate and all the reactants are consumed at the same time, then the fuel cell current is defined as the fuel cell limiting current density i_L . At the limiting current, the reactants pressures are reduced to zero. The relationship between the reactant concentration and the cell potential is shown in (3.25) [2]. The reactants concentrations are depended on the current drawn from the fuel cell.

$$\Delta V = \frac{RT}{nF} \ln\left(\frac{C_B}{C_S}\right) \quad (3.25)$$

C_B is the bulk concentration of the reactant (mol cm^{-3}) and the C_S is the concentration of the reactant at the surface of the catalyst. Equation (3.26) shows the flux of reactant (N) as a function of the concentration gradient .

$$N = \frac{D_e \cdot (C_B - C_S)}{\delta} A \quad (3.26)$$

D_e is the diffusion coefficient $\text{cm}^2 \text{s}^{-1}$, A is the electrode active area (cm^2) and δ is the diffusion distance (cm). In steady state, the rate of the reactant consumption which is equal to N is proportional to the cell current density [2].

$$N = \frac{I}{n_e F} \quad (3.27)$$

n_e is the number of charge and the F is the Faraday's constant. By substituting the (3.26) into the (3.27), the current density i is expressed as a function of the concentration [65].

$$i = \frac{n_e F D_e (C_B - C_S)}{\delta} \quad (3.28)$$

When the cell current is maximum, all reactants are consumed and C_S is zero. From (3.28), the limiting current i_L of the cell is shown in (3.29).

$$i_L = \frac{n_e F D_e C_B}{\delta} \quad (3.29)$$

From (3.25), (3.28) and (3.29), the voltage loss by the concentration can be expressed as shown in (3.30) [65].

$$\Delta V = \frac{R_u T}{nF} \ln \left(\frac{i_L}{i_L - i} \right) \quad (3.30)$$

Due to the uneven distribution of the electrode reaction surface, the limiting current i_L could not consider as a constant value for the entire cell area [2]. Therefore, the empirically formulated equation which is shown in (3.31) is used to determine polarization curve characteristics at high current densities [65].

$$\Delta V_{con} = c_{em} \exp \left(\frac{i_{fc}}{d_{em}} \right) \quad (3.31)$$

$c_{em} = 3 \times 10^{-5} V$ and $d_{em} = 0.125 A cm^{-2}$ are empirical coefficients.

3.3.5 PEM Fuel Cell Operational Voltage

By combining the cell irreversibility with the open circuit cell voltage, the polarization curve shows nonlinear characteristics with respect to the current density as shown in (3.33) [6].

$$V = E - \Delta V_{act} - \Delta V_{ohmic} - \Delta V_{con} \quad (3.32)$$

$$V = 1.229 - 0.85 \times 10^{-3} (T_{fc} - 298.15) + 4.308 \times 10^{-5} T_{fc} \ln (P_{H_2})^{\frac{1}{2}} + \ln (P_{O_2}) - \frac{RT_{fc}}{\alpha F} \ln \left(\frac{i_{fc}}{i_0} \right) - i_{fc} R_{int} + c \exp \left(\frac{i_{fc}}{d} \right) \text{ Volts} \quad (3.33)$$

As we can see from the (3.33), the cell voltage is mainly depended on the cell temperature (T_{fc}), the reactants partial pressures (P_{react}) and the fuel cell current (i_{fc}). The PEM fuel cell is mathematically modelled in Matlab Simulink to identify the fuel cell system's operational characteristics based on the equation (3.33). The 100W PEM fuel

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

Table 3.1: PEM fuel cell system specifications

Parameter	Value
Rated power	100W
Number of Cells	24
Rated performance	14V @ 7.2A
Voltage range	13V- 23V
Stack temperature	65 ⁰ C
Nominal Stack efficiency	40%

cell specifications are shown in table (3.1). Figure (3.5) shows the PEM fuel cell developed in Simulink.

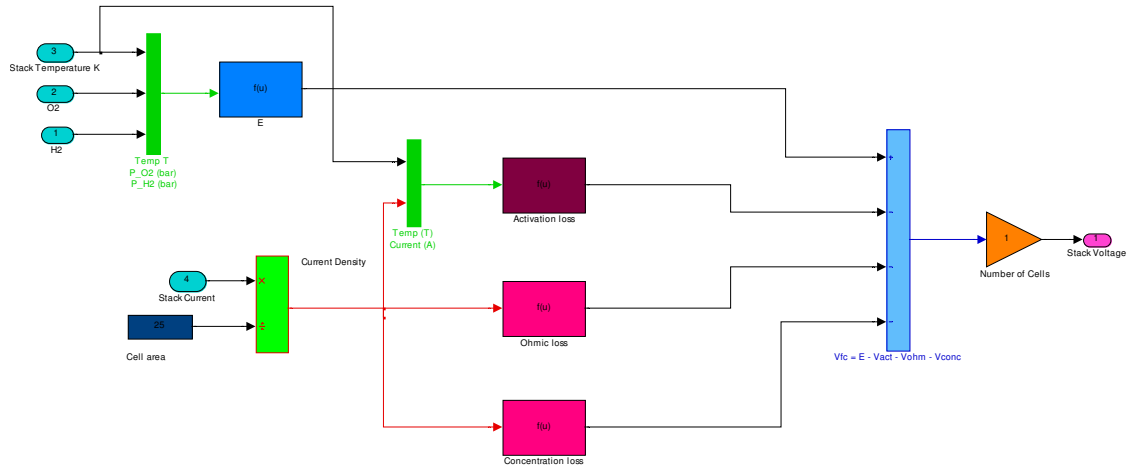


Figure 3.5: Simulink model of the PEM fuel cell

The cell temperature is a dominant factor for deciding the cell potential due to the exponential characteristics of the exchange current density. The equation (3.14) proved that the increase in the cell temperature reduces the cell potential. However, the increases in the cell temperature maximize the exchange current density. Hence the net cell potential has improved. Figure (3.6) shows the cell voltage gained by varying the temperature from 298.15K to 308.15K.

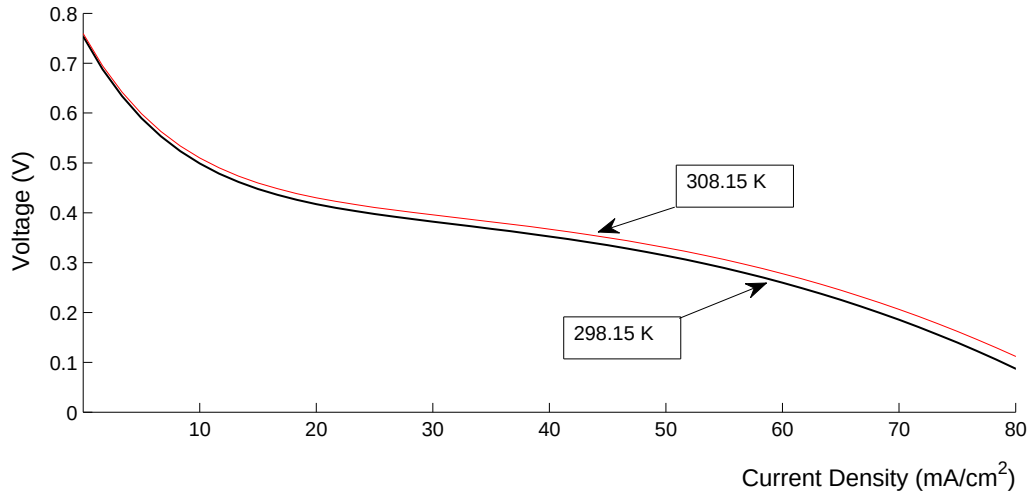


Figure 3.6: *Effect of the cell temperature to the cell potential*

3.4 Cathode Dynamics

The cathode dynamic of the fuel cell is an important process compared with the anode dynamic. In the cathode, the oxygen reduction reaction is comparatively slower than the anode reaction. The oxygen mass flow rate, the amount of oxygen consumed and the partial pressure of the oxygen are considered to determine the optimum air flow rate to the cathode. The effects from the oxygen partial pressure and the oxygen concentration to the cell potential are higher than the hydrogen oxidization reaction [65]. In order to control the cell parameters such as the oxygen concentration and the pressure, the air flow rate and the air supplying system requirements are analyzed. A proper air supplying system should prevent the oxygen starvation at the cathode and dynamically controls the air flow rate according to the load current variations.

3.4.1 Air Flow Rate

The fuel cell inlet reactants flow rates should be higher than the rate of reactants consumed. The oxygen concentration is depended on the flow rate of the oxygen supply. If the air is used instead of the pure oxygen, the air supplying system should maintain the relevant stoichiometry at the cathode side. In most cases, by increasing the inlet air flow rate, the cathode oxygen concentration is increased. However, the high air flow

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

rate increases the cell water removal process. When the fuel cell current is increased, the reaction rate is accelerated and generates extra water in the cathode. The increased in air flow rate removes the extra water accumulated in the cathode and the membrane hence consequently improves the cell performances. However, the increased in air flow beyond the certain level may cause drying effect to the membrane and disturbs to the proton movements. Therefore, the changes in air flow rate should monitor carefully to prevent the cell drying. The most PEM fuel cell systems which are designed for the automobile applications are built with air compressors instead of a pressurized oxygen tank. In some cases, the air supplying system is consisted of an air blower instead of an air compressor depending on the fuel cell power capacity. The air pressurization process raises another concern over the temperature increase compressed air. However, the oxygen concentration and the pressure inside the fuel cell stack should be maintained at an optimum value to get the maximum cell power output.

From Faraday's law, the amount of the oxygen consumed is determined in (3.34) [65].

$$\dot{N}_{O_2} = \frac{i_{fc}}{4F} \quad (3.34)$$

$\dot{N}_{O_2}$ is the oxygen consumption rate in $mol s^{-1}$. For the analysis of the oxygen mass flow rate, assumes that the oxygen gas behaves similar to the ideal gas. In addition to that, assumes the fuel cell temperature is a constant for the whole process and is controlled by a separate controller. The gas pressure and the flow rate dropped by the flow channels are ignored. The mass flow rate of the reacted oxygen $\dot{m}_{O_2}$ is shown in (3.35) [2].

$$\dot{m}_{O_2,reacted} = \frac{i_{fc}}{4F} M_{O_2} \quad (3.35)$$

M_{O_2} is the molar mass of the oxygen. the amount of oxygen reacted is considered for the compressor power analysis in the next section.

3.5 Air Supply System

The increase in the oxygen partial pressure of the fuel cell affects to the Nerst equation as well as to the oxygen concentration of the fuel cell and increases the cell net voltage gain. The cell temperature and the cell humidity dynamics rates are relatively slower than the cell pressure and the concentration dynamics [62]. Therefore, assumes that the cell temperature, the humidity and the hydrogen supply are controlled by separate control systems. The air supply system is mainly consisted with a compressor chamber and a motor drive.

3.5.1 Air Pressurization

Air is pressurized to the optimum level in order to achieve the maximum cell voltage by minimizing the activation loss and maximizing the Nerst voltage gain. Obviously, the air pressurization process is also consumed additional power. The relationship between the air pressure, the air usage and the compressor power is determined to identify the net voltage gained from the cell. Equation (3.36) shows the power needed for the adiabatic air compression from pressure Pr_1 to Pr_2 [2].

$$P_{com} = \dot{m}_{air} c_p \frac{T}{\eta_m \eta_c} \left[\left(\frac{Pr_2}{Pr_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \text{watts} \quad (3.36)$$

c_p is specific heat of the air $= 1.005 \text{ kJ kg}^{-1} \text{ K}^{-1}$ at 298 K , T is the temperature K , η_c and η_m are compressor and compressor motor efficiencies. The air concentration is maintained higher than the fuel cell stoichiometry λ to prevent the oxygen starvation. From (3.35), the relationship between the oxygen consumption rate ($\dot{m}_{O_2}$), the cell power P_c and the cell voltage V_c are derived in (3.37) [2].

$$\dot{m}_{O_2} = \frac{P_c}{4F \times V_c} M_{O_2} \quad (3.37)$$

The cell power can be expressed as a function of the cell voltage and the cell current ($P_c = V_c \times i_{fc}$). The air to oxygen percentage is approximately 21%. The air consumption rate $\dot{m}_{air}$ is determined in (3.38).

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

$$\begin{aligned}\dot{m}_{air} &= \frac{28.97 \times 10^{-3} kgmole^{-1} P_c \times \lambda}{0.21 \times 4 \times V_c \times 96495 C/mol} kgs^{-1} \\ \dot{m}_{air} &= 3.57 \times 10^{-7} \frac{P_c \lambda}{V_c} kgs^{-1}\end{aligned}\quad (3.38)$$

From (3.38) and (3.36), the power consumed by the compressor is shown in (3.39) [2].

$$P_{com} = 3.58 \times 10^{-4} \times \frac{T}{\eta_m \eta_c} \left[\left(\frac{Pr_2}{Pr_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \lambda n i_{fc} \quad (3.39)$$

n is the number of fuel cells. The power consumed by the compressor is divided by the fuel cell current and the number of cells and obtained the voltage loss per cell as shown in (3.40) [2].

$$\Delta V_{com} = 3.58 \times 10^{-4} \times \frac{T}{\eta_m \eta_c} \left[\left(\frac{Pr_2}{Pr_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] Volts \quad (3.40)$$

3.6 Fuel Cell Net Power

The PEM fuel cell system net power output is the power difference between the power generated by the fuel cell system and the power consumed by the auxiliary devices mainly the air compressor. The fuel cell air supply system should control in order to prevent the oxygen starvation. When the load current is changed, the air pressure and flow rates should be changed to the optimum value to generate the maximum net fuel cell power output. The fuel cell system net power output $P_{fc_{net}}$ can be defined as shown in (3.41).

$$P_{fc_{net}} = P_{fc} - P_{com} \quad (3.41)$$

P_{fc} is the power generated from the fuel cell and the P_{com} is the power consumed by the compressor.

3.6.1 Voltage Gain

In the previous section, the cell voltage gain due to the increase in the air mass flow rate and the pressure is discussed. In the literature, an empirical equation (3.42) has formed to represent the voltage gain as a combination of the pressure effect and the increase in exchange current density [2] [65]. The voltage gained due to the pressure increase from P_1 to P_2 is,

$$\Delta V_{gain} = C_g \ln \left(\frac{P_2}{P_1} \right) \quad (3.42)$$

C_g is an empirically derived constant and depends on the fuel cell system power capacity. The power gained from the n number of fuel cell at current i is described in (3.43) [2].

$$P_{gain} = C_g \ln \left(\frac{P_2}{P_1} \right) n \cdot i \text{ Watts} \quad (3.43)$$

For the 100W PEM fuel cell, $C_g = 0.12$.

3.6.2 Net Power Gain

The fuel cell system net power gain (P_{net}) is the power difference between P_{gain} and P_{com} . The net power output of the PEM fuel cell system is a function of the pressure ratio as shown in (3.44) [2]. The efficiencies of the compressor motor (η_m) and the compressor (η_c) are considered as the 92% and 88%.

$$\begin{aligned} P_{net} &= P_{gain} - P_{com} \\ P_{net} &= n \cdot i \left[C_g \ln \left(\frac{P_2}{P_1} \right) - 3.58 \times 10^{-4} \times \frac{T\lambda}{\eta_m \eta_c} \left\{ \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \right] \text{ Watts} \end{aligned} \quad (3.44)$$

The figure (3.7) shows the variation of the P_{net} with the pressure ratio $\frac{P_2}{P_1}$ in different current densities. For a certain level of the pressure ratio, the fuel cell net power is increased and later the P_{net} is gradually decreased due to the increase in the compressor

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

power. When the current density is increased, the maximum net power gain $P_{net,max}$ can be obtained at lower pressure ratio. The optimum pressure ratio is varied between 1.8 and 2.25, during the fuel cell current changes from 1A to 8A. The optimum compressor power (P_{com}^{op}) can be determined from the equation (3.39) by substituting the optimum pressure ratio and the fuel cell current.

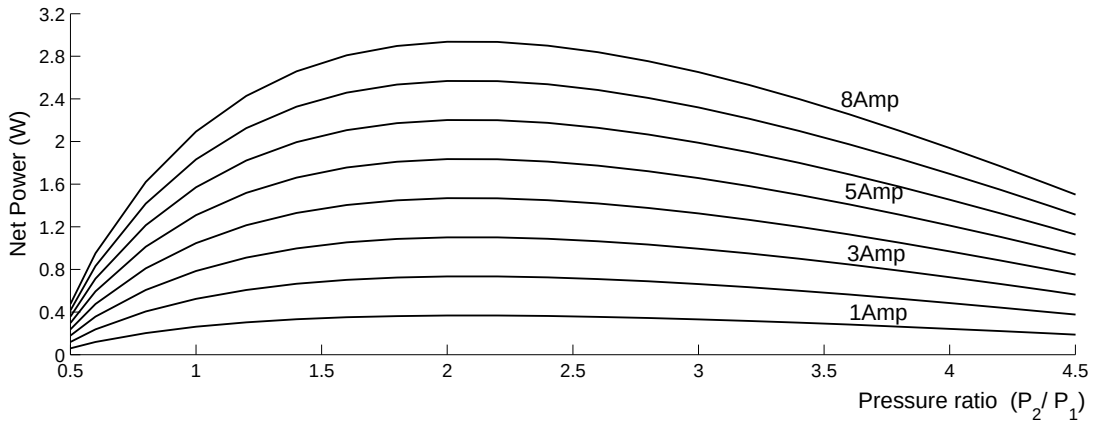


Figure 3.7: Fuel cell net power variations with the pressure ratio

Table (3.2) shows the optimum compressor power which produces the maximum fuel cell net power output at the different fuel cell currents. By using the curve fitting analysis, the optimum compressor power is obtained as a cubic function of the fuel cell current as shown in equation (3.45). The optimum compressor power at the different fuel cell current is illustrated in figure (3.8).

$$\begin{aligned}
 P_{com}^{op} &= f(I_{fc}) \\
 P_{com}^{op} &= -0.0035I_{fc}^3 - 0.007I_{fc}^2 + 1.6I_{fc} + 0.02
 \end{aligned} \tag{3.45}$$

The optimum compressor power can be represented as the optimum compressor motor voltage by considering the relationship of the compressor and the compressor motor characteristics. The compressor map is used to determine the optimum air flow rates for the different pressure ratios. In order to generate the optimum pressure ratio, the compressor motor speed is changed according to the fuel cell current variation. By varying

Table 3.2: Optimum compressor power for different FC current

FC current (A)	Optimum compressor power (W)
1	1.67
2	3.1
3	4.5
4	5.9
5	6.92
6	7.61
7	8.18
8	8.48

the terminal voltage of the motor, the required voltage for optimum air pressure can be achieved.

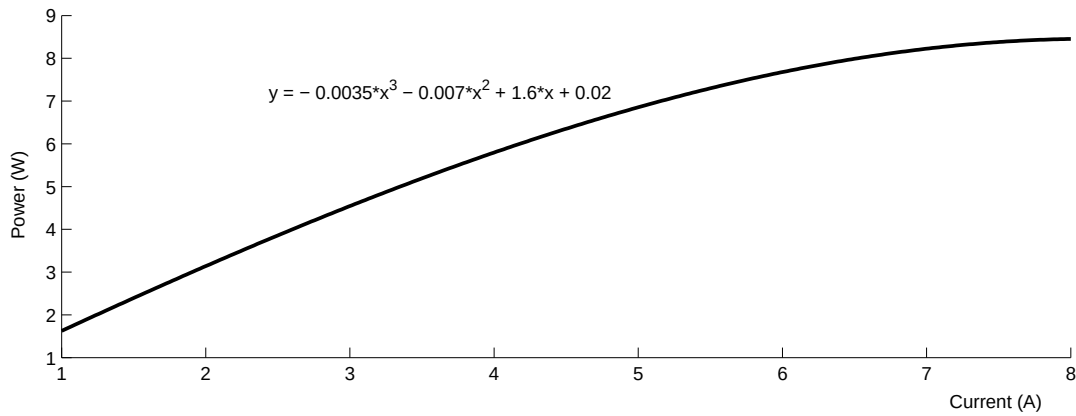


Figure 3.8: Optimum compressor power

The maintaining the optimum compressor power to obtain the maximum fuel cell net power output during the mission is a control challenge for the developers. In the literature, the control methodologies such as feedforward control , optimal control and model predictive control were used to control the air supplying system of the fuel cell. In this research, an adaptive control architecture is introduced in chapter (7) to control the compressor power.

3. PEM FUEL CELL SYSTEMS AND CATHODE DYNAMICS

UAV Propulsion Power

Requirements

Long endurance unmanned electric aerial vehicles (UEAV)s emerge as a modern aviation technology due to the advanced developments in the electric propulsion systems. The electric power sources such as Proton Exchange Membrane fuel cells (PEMFCs) and Li-Ion batteries show potential to replace conventional combustion engines from the UAVs due to higher energy and power densities. The fuel economy and endurance capability of the aerial vehicle can be improved considerably by introducing the hydrogen powered PEM fuel cell system into the propulsion system. In addition to that, the aerospace electric propulsion is considered as an environment friendly aviation concept due to stealth operation and minimum carbon emission.

The propeller driven piston engine aircraft efficiency is low at higher speed operation and much noisier than the low speed operation [66]. The wax deposit inside the fuel storage at low temperature is another drawback of the piston engine driven aircraft [66]. As the result of these drawbacks, the aircraft manufactures developed the propeller driven aircrafts with low rpm piston engines and variable pitch propellers. However, after the emerged of the electric propulsion with the brushless DC motors, the potential to develop the higher speed aircraft propulsion systems have increased. In the electric

4. UAV PROPULSION POWER REQUIREMENTS

powered aircrafts, the high speed PMBL DC motors can operate at higher efficiencies than the piston engines and can eliminate the requirement of the low speed propeller operation.

The main objective of the fuel cell based electric propulsion system is to increase the aircraft endurance capacity compared to the other types of power plants. In the automobile industry, the fuel cell electric vehicles with hybrid configuration extend the vehicle range per gallon significantly compared to the combustion engine vehicles. The same hybrid technology is proposed to the fuel cell powered UAV with an optimized air control system. In this chapter, the primary stages of the conceptual aircraft design process are considered to identify the critical parameters values and the propulsion power requirements in different flying conditions.

4.1 UAV Mission Profile

An intelligence, surveillance and reconnaissance (ISR) mission with increased endurance and range capabilities is considered for the aircraft propulsion system and power plant design processes. The mission involves several flying modes such as aircraft take-off, climb, cruising, endurance, descent and landing. Figure (4.1) shows the ISR mission view including the all possible flying modes. The fuel cell powered UAV (FC-UAV) long endurance mission is started with the take-off mode and climb lasts until the cruising altitude is achieved. Then the FC-UAV starts to fly at cruising speed towards the target destination. When the FC-UAV is closer to the target, the aircraft altitude is lowered for better surveillance and reconnaissance. During the surveillance mission, the aircraft endurance mode is activated to save the energy. When the aircraft finishes its target acquisitions, the FC-UAV flies at cruising mode to reach the landing destination. It is assumed that, when the FC-UAV loitering and landing, the propulsion system power demand is similar to the cruising power. The FC-UAV flying altitudes and the speeds are depended on the available power for the ISR mission. The aircraft take-off and the initial climb powers cause a significant impact to the power plant designing process which needs higher power and energy capacities with optimized power to weight ratio. The proposed hybrid power system is consisted with a 100W PEM fuel cell system and a 3.1L hydrogen gas storage to supply the power for 3 hours duration. The aircraft

and the power plant design specifications are compared with the similar configurations developed in [67] and [68].

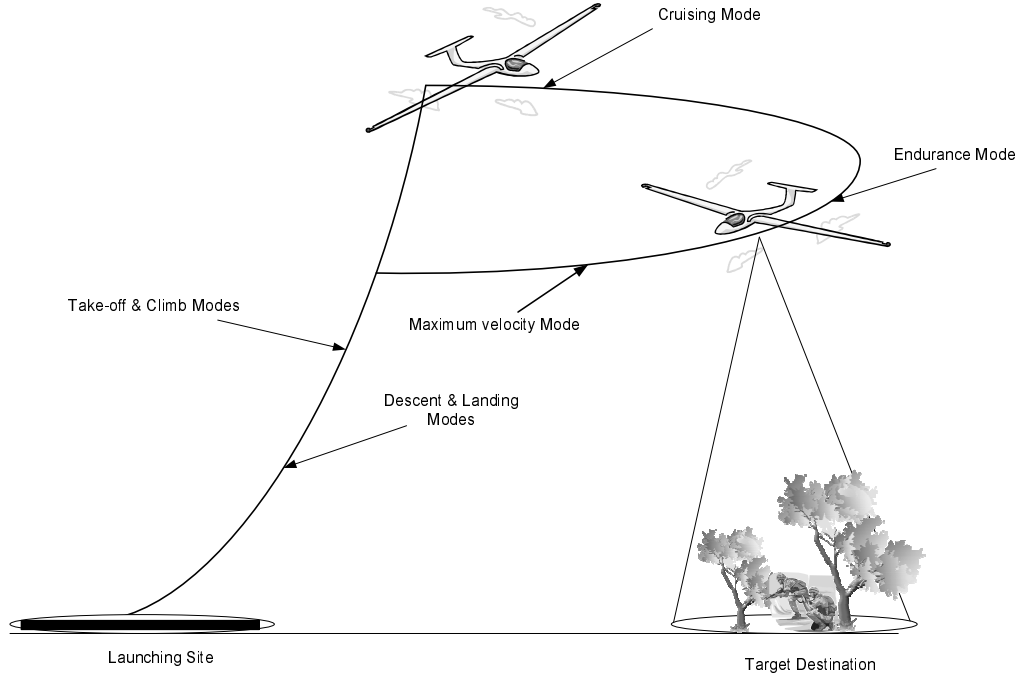


Figure 4.1: Aircraft mission scenario

4.1.1 Long Endurance Mission

The long endurance mission which has 3 hours airtime is proposed to identify the propulsion requirements. Initially, 5 minutes start-up period is allocated for the fuel cell preparation. Then, the FC-UAV starts to take-off and reaches 600m altitude within the 10 minutes duration with $1ms^{-1}$ climb rate. Then the propulsion system cruising mode is activated and performs level flight operation for 20 minutes period at cruising speed $15ms^{-1}$. Then, the FC-UAV lowered to 300m altitude and switches to the endurance mode. The flight endurance mode is maintained for 2 hours with $11ms^{-1}$ flying speed. At the endurance mode, the flight displacement is assumed as zero and considered the flight is circling around the target. Then the UAV returns back to the launching site at cruising velocity $15ms^{-1}$ without changing the altitude. Eventually, the landing power mode is activated for 10 minutes period and the aircraft taxing period is 5 minutes. The long endurance mission altitude and the speed variations are

4. UAV PROPULSION POWER REQUIREMENTS

shown in figure (4.2) and (4.3).

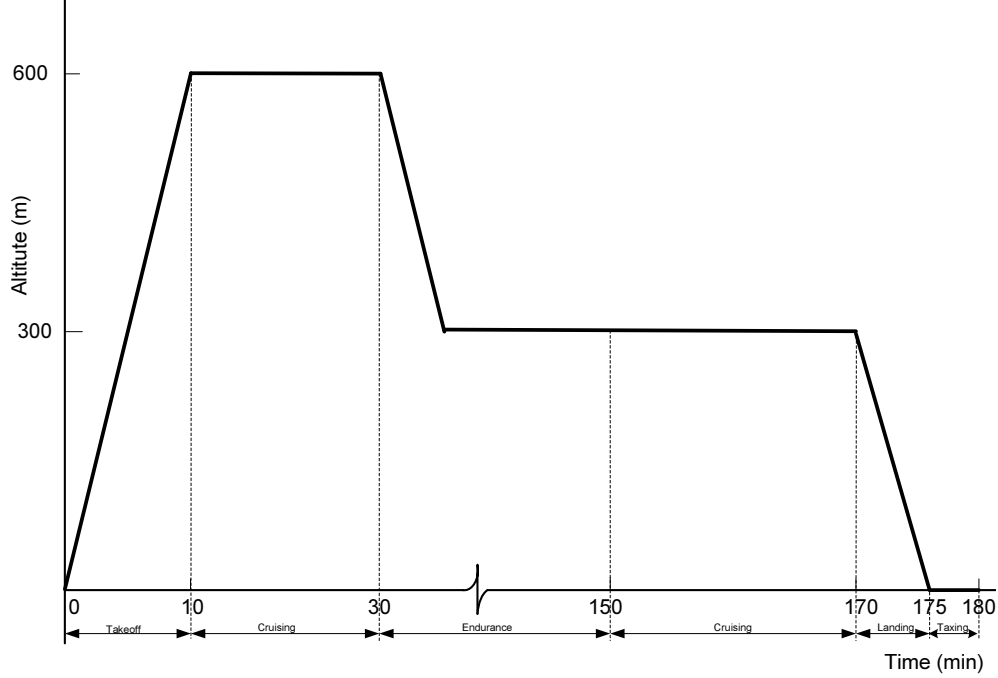


Figure 4.2: FC-UAV altitude variations during the long endurance mission

4.2 UAV Performance Requirements

The propulsion power requirement during the mission is depended on the flying modes of the aircraft such as the aircraft take-off, the climb, the cruising, the endurance, the descent and the landing. Initially, the aircraft critical parameters are analyzed for a specific ISR mission. The hybrid power plant must satisfy the UAV performance requirements such as aircraft speed, altitude and endurance time to complete the ISR mission successfully. Therefore, the power plant power capacity is decided based on the performance requirements for the specified ISR mission. Table (4.1) shows the proposed FC-UAV performance specifications suitable for the PEM FC/ Li-Ion battery power plant. Based on these performance requirements, the power required for take-off, maximum speed, maximum rate of climb and endurance mode are determined in following sections.

The hybrid electric UAV (HEUAV) which described in [67] is considered for the FC-UAV propulsion analysis due to the similarities in design process. The proposed FC-

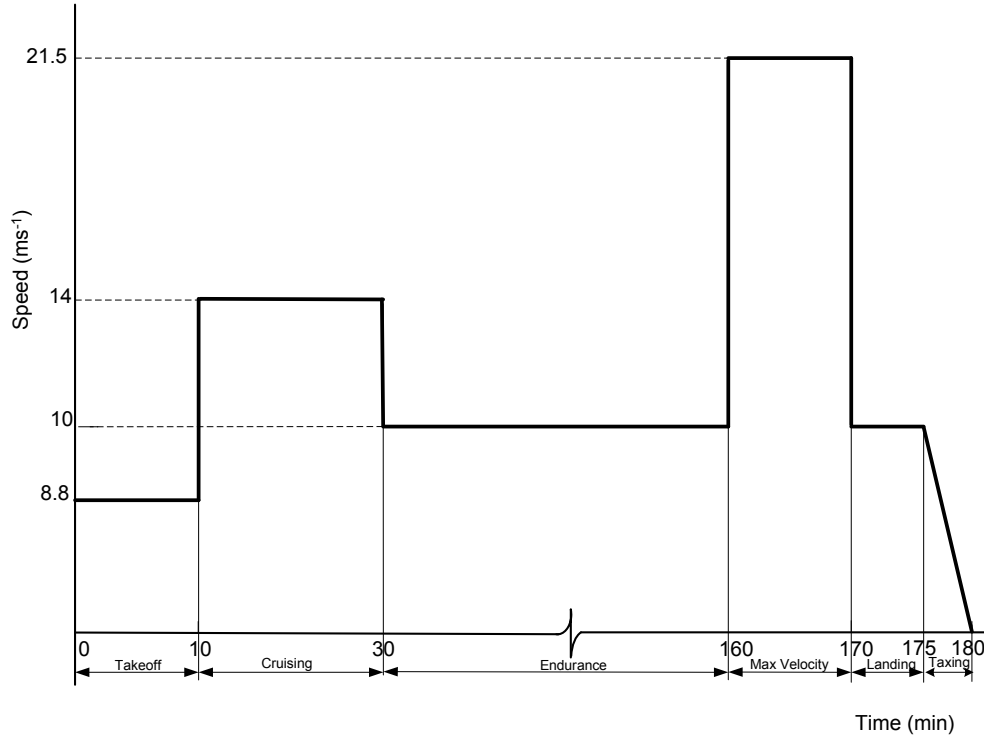


Figure 4.3: FC-UAV speed variations during the long endurance mission

UAV is designed to perform low altitude operation while operating at a higher cruising speed. Therefore, the wing loading (W/S) should increase and the lift coefficient (C_L) should be sufficient for 600m altitude. The FC-UAV stall speed V_{stall} which is a function of the wing loading (W/S) and the C_L is selected as $8ms^{-1}$ based on the specifications defined in [67].

The airfoil NACA 23012 data set which is described in [3] is used for the critical parameters analysis. The FC-UAV maximum lift coefficient for the airfoil NACA 23018 is selected as $C_{Lmax} = 1.25$ from [3]. The aircraft take-off distance is limited to 20m for the rapid take-off. In fact, the most military UAVs are deployed by using the mobile launching platform rather than from the specified runway. The airborne distance for clear the obstacle h_{tf} of the FC-UAV is considered 2m which is similar to the launching system ramp-end height relative to the ground.

4. UAV PROPULSION POWER REQUIREMENTS

Table 4.1: UAV Performance Requirements

Parameter	Value
Endurance speed	10 ms^{-1}
Maximum speed	21.5 ms^{-1}
Cruise speed	14 ms^{-1}
Maximum operating altitude	600 m
Rate of climb (R/C)	1 ms^{-1}
Stall speed (V_{stall})	8 ms^{-1}
Take-off distance (d)	20 m
Maximum Lift coefficient ($C_{L_{max}}$)	1.25
Zero lift drag coefficient ($C_{D,0}$)	0.036
Maximum L/D ratio	16.4

4.3 Total Aircraft Weight

The total aircraft weight W is the combination of the subsystems weights such as glider weight, propulsion system weight, fuel weight etc. In addition to the design specification described in [67], the FC-UAV developed by [68] is considered for this application due to the similarities in the used PEMFC system and the proposed airframe. By assuming the same glider used in [68] is fitted for the proposed FC-UAV, the aircraft total mass can be approximated to 7.75 kg . The Li-Ion battery, PMBLDC motor, three phase inverter, unidirectional converter and the bidirectional converter weights are taken from the experimental setup which developed for this research. Table (4.2) shows the weight distribution of the proposed FC-UAV. The 100W PEMFC system specifications which is developed by [69] are used for the analysis. The hydrogen tank is selected from the Pstear UAV [70] which has 3.1 litre volume and the 1.95 kg total mass including 65g compressed hydrogen. Assumes that the fuel cell system and the hydrogen cylinder

Table 4.2: *UAV mass distribution*

Component	Mass (kg)
PEM fuel cell	0.9
Hydrogen gas tank	1.95
FC Controller	0.45
Regulators and Tubes	0.25
Glider	2.6
Li-Ion battery	0.95
PMBL DC motor	0.3
Three phase inverter	0.1
Power converters	0.25
Total Mass	7.75

can be installed into the airframe which described in [68] without major modifications. Therefore, the volume constraints are not considered in this fuel cell installation to the UAV fuselage.

4.4 Take-off Performances

The aircraft takeoff power is a crucial factor for the power plant design process. The relationship between the aircraft takeoff power (P_{tf}), thrust (T_r) generated by the propeller and aircraft speed (V_{fl}) is shown in equation (4.1) [3]. By increasing the propeller thrust, the take-off power can be improved. The minimum power required for the UAV take-off is determined by using aerodynamics equations described [3].

$$P_{tf} = T_r V_{fl} \quad (4.1)$$

4. UAV PROPULSION POWER REQUIREMENTS

In appendix (A.1), the maximum lift coefficient during the take-off period ($C_{L_{max}}^{tf}$) period is obtained as 2.43. The aircraft wing loading ($\frac{w}{s}$) during the take-off and at the speed of $V_{stall} = 8ms^{-1}$ at sea level is determined as $95.25Nm^{-2}$ in appendix (A.2). The aircraft thrust to weight ratio during the take-off period is derived in appendix (A.3). The take-off distance can be illustrated as the combination of the rolling distance d_g and the airborne distance d_a as shown in figure (4.4) [3]. In the appendix (A.3), the equation (A.18) shows that the take-off thrust to weight ratio is $\frac{T}{W} = 0.370$.

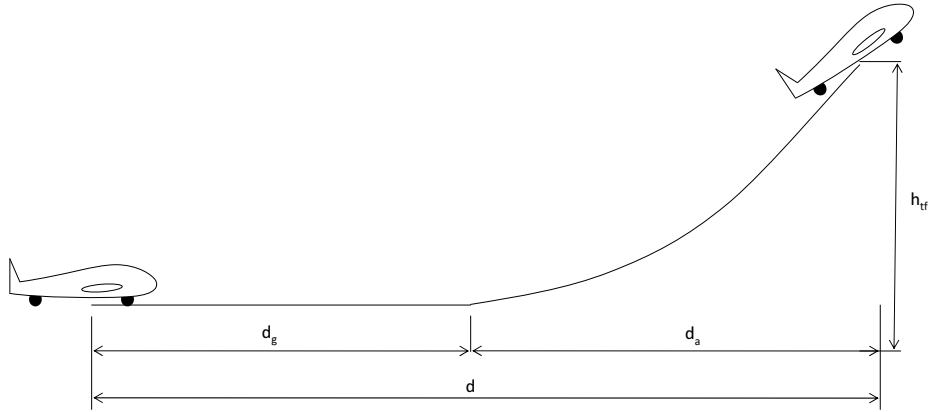


Figure 4.4: Aircraft rolling and airborne distance

From (4.1) and (A.18), the power required for the UAV takeoff can be expressed as in (4.2) [3],

$$P_{tf} = \frac{T_r}{W} W_0 V_{tf} \quad (4.2)$$

W_0 is the aircraft take-off weight obtained from the table (4.1). V_{tf} is the takeoff velocity and it equals to lift-off velocity which has $1.1V_{stall}$ speed.

$$V_{tf} = 1.1V_{stall} \quad (4.3)$$

$$V_{tf} = 1.1 \times 8$$

$$V_{tf} = 8.8ms^{-1} \quad (4.4)$$

By substituting the $\frac{T}{W}$, W_0 and V_{tf} into (4.2), the minimum power required for the take-

off is obtained in (4.6),

$$P_{tf} = 0.370 \times (7 \times 9.81)N \times 8.8ms^{-1} \quad (4.5)$$

$$P_{tf} = 223.5W \quad (4.6)$$

4.4.1 Rate of Climb

After the aircraft is take-off, the operating power mode is switched to the climb power. Assumes that the aircraft initial climb rate $1m/s$ is the maximum climb rate defined for the aircraft after the take-off mode. The power required during the maximum rate of climb speed is an essential factor for the power plant sizing. Figure (4.5) shows the forces distribution when the aircraft is climbing. By assuming the thrust T_r and the

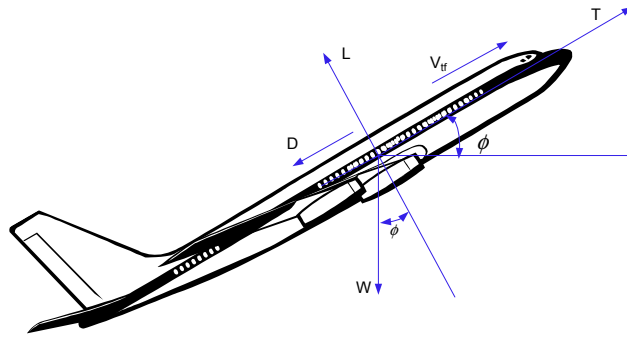


Figure 4.5: Aircraft force distribution during the climb

flight speed (V_{fl}) are in the same direction, the rate of climb (R/C) can be expressed as shown in (4.7) [3]. From the figure (4.5),

$$R/C = V_{fl} \sin(\Phi) \quad (4.7)$$

$$T_r - D - W \sin(\Phi) = 0 \quad (4.8)$$

From (4.7) and (4.8), the R/C is obtained,

$$R/C = V_{fc} \frac{(T_r - D)}{W} \quad (4.9)$$

4. UAV PROPULSION POWER REQUIREMENTS

D is the drag caused by the aircraft. The power available of the aircraft and the power needed to overcome the drag is defined as the excess power (P_{ex}) of the power plant [3]. The proposed FC-UAV limits the maximum available power to 150W except initial climb.

$$R/C = \frac{P_{ex}}{W} \quad (4.10)$$

However, for the propeller driven plane, assumes that the aircraft is climbed at the maximum rate of climb during the initial climb. The maximum rate of climb is defined as shown in (4.11) in [3].

$$(R/C)_{max} = \frac{\eta_{pr}P}{W} - \left(\frac{2}{\rho_{\infty}} \sqrt{\frac{K}{3C_{D,0}}} \frac{W}{S} \right)^{\frac{1}{2}} \frac{1.155}{(\frac{L}{D})_{max}} \quad (4.11)$$

K is the proportionality constant and $C_{D,0}$ is the zero lift drag coefficient. Maximum lift to drag ratio $(\frac{L}{D})_{max}$ is defined in (4.12) [3].

$$\left(\frac{L}{D} \right)_{max} = \sqrt{\frac{1}{4C_{D,0}K}} \quad (4.12)$$

From table (4.1), $(\frac{L}{D})_{max} = 16.4$ and $C_{D,0} = 0.036$ are substitute to (4.12) and K is obtained.

$$K = \frac{1}{4C_{D,0}(\frac{L}{D})_{max}^2} \quad (4.13)$$

$$K = 0.0258 \quad (4.14)$$

The maximum climb rate is limited to 1m/s as mentioned in the performance requirement and assumes that the W is equal to W_0 by neglecting the amount of fuel consumed during the aircraft take-off [3]. The propeller efficiency η_{pr} is considered 0.80 and efficiency derivation will be discuss in section (4.7). From the equation (4.11), the power

required during the maximum climb rate is derived in (4.15),

$$P_{climb}^{max} = 154.2W \quad (4.15)$$

4.5 Aircraft Level Flight Operation

When the FC-UAV reaches the maximum altitude which is $600m$, the flight proceeds without increase in altitude. In the level flight operation, climb and roll angles are zero for the entire period. At this stage, the aircraft thrust (T) is equal to drag (D) and the aircraft weight is considered as mid-cruise weight ($W_{MC} = 0.9039W_0$). The level flight operational conditions are applied to the aircraft cruise mode as well as the endurance mode. The aircraft power requirement during the level flight operation can be expressed in (4.16) [3].

$$P_{cr} = \sqrt{\frac{2W_{MC}^3 C_D^2}{\rho_\infty S C_L^3}} \quad (4.16)$$

W_{MC} is the mid-cruise weight which assumes the fraction of the take-off weight ($W_{MC} = 0.9039W_0$). The aircraft wing area S , the lift coefficient C_L and the drag coefficient C_D are derived in equations (4.19)(4.22) and (4.25) at velocity $14ms^{-1}$. The air density at altitude $600m$ is $1.156kg/m^{-3}$.

$$S = \frac{W_0}{\frac{W}{S}} \quad (4.17)$$

$$S = \frac{7.3 \times 9.81N}{95.25Nm^{-2}} \quad (4.18)$$

$$S = 0.752m^2 \quad (4.19)$$

$$C_L = \frac{2W_{MC}}{\rho_\infty V_{cr}^2 S} \quad (4.20)$$

4. UAV PROPULSION POWER REQUIREMENTS

$$C_L = \frac{2 \times 64.7N}{1.156kgm^{-3} \times (14ms^{-1})^2 \times 0.753m^2} \quad (4.21)$$

$$C_L = 0.76 \quad (4.22)$$

$$C_D = C_{D,0} + KC_L^2 \quad (4.23)$$

$$C_D = 0.036 + 0.0258 \times (1.19)^2 \quad (4.24)$$

$$C_D = 0.051 \quad (4.25)$$

From the equation (4.16), the power required by the cruise mode at velocity $14ms^{-1}$ is obtained in (4.26).

$$P_{cr} = \sqrt{\frac{2 \times (64.7N)^3 \times (0.051)^2}{1.156kg/m^{-3} \times 0.751m^{-2} \times (0.76)^3}} \quad (4.26)$$

$$P_{cr} = 60.1W \quad (4.27)$$

When the aircraft is flying at endurance velocity which is $10ms^{-1}$, at $300m$ altitude in the level flight operation, the lift coefficient and the drag coefficient are obtained as 1.49 and 0.093 from the (4.22) and (4.25). The aircraft weight is considered as the mid cruise weight. By using the equation (4.16), the power required for endurance mode operation at $10ms^{-1}$ is obtained as $40.5W$

4.6 Mission Maximum Velocities

The aircraft mission velocity is depended on the power availability of the power plant. During the level flight operation of the long endurance mission, the aircraft flying velocity is varied from cruise mode to endurance mode and again moves to the cruise mode. Depending on the power availability, the speed of the aircraft can be changed according to the equation (4.16). The power demanded by the propulsion system in different speeds is plotted in figure (4.6). After the stall speed $8ms^{-1}$, the power required by the propulsion system is increased with the velocity. During the cruise mode, the

propulsion power is supplied by only using the PEM fuel cell system up to $100W$. After the electrical and the mechanical losses, the power available for maximum cruise speed is limited to $62W$. At this stage, the corresponding maximum cruise speed is $14ms^{-1}$. In the hybrid power configuration, the maximum power availability is risen up to $223.5W$ and the aircraft maximum velocity is limited to $21.5ms^{-1}$. However, in this analysis, the power available for the maximum velocity is limited to $150W$.

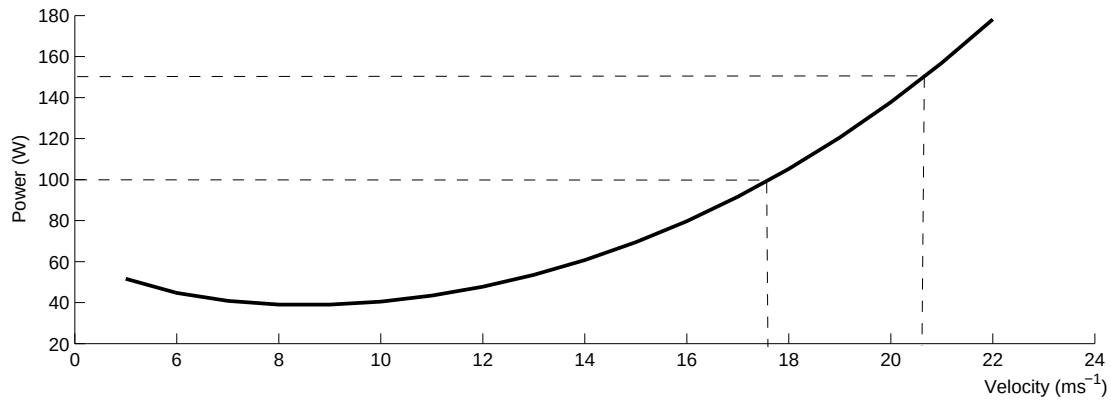


Figure 4.6: Aircraft power required for different speeds

4.7 Propeller Efficiency and Motor Shaft Power

The propulsion power requirements for the different flying modes were determined in the equations (4.6), (4.15), (4.19) and (4.26). Those power values except the maximum rate of climb power represent the required propeller thrust power. The power losses from the propeller need to be considered to obtain the motor shaft power requirement. The propeller efficiency can be represented as the ratio between the the output power of the propeller and the input power from the motor shaft. However, propeller efficiency is not a constant and it varies with the propeller rotating speed (N rev/sec) and the aircraft speed V_{∞} . The relationship between the aircraft speed and the rotating speed can be presented as shown in equation (4.28).

$$J_r = \frac{V_{\infty}}{\pi N D_p} \quad (4.28)$$

4. UAV PROPULSION POWER REQUIREMENTS

J_r is the advance ratio and it represents the distance of the aircraft advance per propeller rotating cycle. D_p is the propeller diameter. The propeller thrust coefficient and the power coefficient which are shown in equations (4.29) and (4.30) are another important factors for the propeller performance analysis.

$$C_T = \frac{T_r}{\rho_\infty N^2 D_p^4} \quad (4.29)$$

$$C_Q = \frac{Q}{\rho_\infty N^2 D_p^5} \quad (4.30)$$

ρ_∞ is the air density and the T_r is the thrust generated by the propeller. Q is the torque applied by the propeller to the motor shaft.

The relationship between the torque applied and the power supplied by the motor can be expressed as shown in (4.31). The propeller power output is represented in (4.1) as a function of the aircraft speed and the thrust generated.

$$P_{in} = 2\pi NQ \quad (4.31)$$

$$P_{out} = T_r V_\infty \quad (4.32)$$

The relationship between the propeller efficiency, the propeller coefficients and the advance ratio is shown in equation (4.33).

$$\begin{aligned} \eta_{pr} &= \frac{T_r V_\infty}{2\pi NQ} \\ \eta_{pr} &= \frac{J_r C_T}{2\pi C_Q} \end{aligned} \quad (4.33)$$

4.7.1 DC Motor and Propeller Matching

The equilibrium rotating speed of the motor (N) occurs when the motor induced torque (T_e) and the torque applied by the propeller (Q) are equal as shown in (4.34). $V_D C$ is

the terminal voltage of the motor.

$$Q(V_{\infty}, N) = T_e(V_{DC}, N) \quad (4.34)$$

The selection of the motor and the motor characteristics are discussed in chapter (5) section (2). The induced torque of the motor is a function of the terminal voltage of the motor and the angular speed of the motor.

Lets consider the aircraft velocities during the take-off power, cruising power and the maximum velocity power for the analysis of the propeller efficiency. During the take-off, the power requirement is $223.5W$ and the aircraft flying velocity is the $8.8ms^{-1}$. The cruising and the maximum velocity power requirements are $60.1W$ and the $150W$ respectively. The aircraft speed for these two modes are $14.1ms^{-1}$ and $21.5ms^{-1}$.

The propeller efficiency is varied with aircraft speed. Hence, for the each flying power mode, the propeller operating efficiency need to be determined for the different angular velocity of the propeller. For the specific power mode, the angular velocity of the motor is varied and identified the optimum angular velocity of the motor which gives the maximum efficiency. The maximum operating efficiency is determined based on the equations (4.28),(4.29),(4.30) and (4.33). The simulation models were developed and obtained the efficiencies variations with the advance ratio as graphically represented in figures (4.7),(4.8) and (4.9) for each power mode.

The torque Q is determined from the motor torque equations which are described in chapter (5). The equilibrium speed can be obtained when the applied torque and the motor induced torque are equal. The motor induced torque (T_e) is substituted to the (4.30) as the applied torque by the propeller. It has assumed that effect from the rotor inertia and the viscous friction are minimum during the high speed operation. The motor terminal voltage is $24V$ and the rotor angular velocity is varied between $1000rpm$ and $4500rpm$. The selected propeller has $0.12m$ diameter.

Figure (4.7) shows the variation of the propeller efficiency with advance ratio during the take-off power mode. The maximum efficiency 0.84 can be obtained at the advance ratio 0.75 . At this stage angular velocity of the motor is $1867.4rpm$. Similarly, from the figures (4.8) and (4.9), the maximum efficiencies for the cruise and the maximum

4. UAV PROPULSION POWER REQUIREMENTS

velocity mode are obtained as 0.71 and 0.60 at 3183rpm and 4277rpm angular velocities respectively.

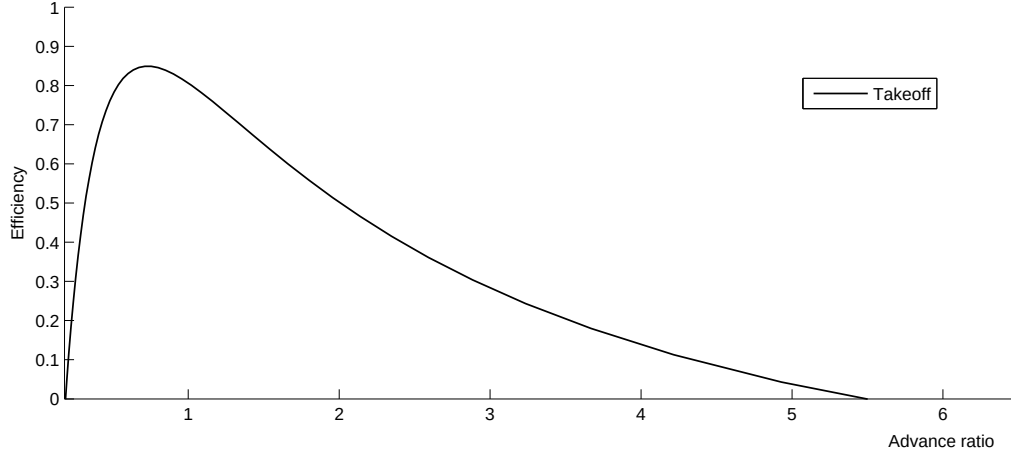


Figure 4.7: Propeller efficiency variation with the advance ratio during the take-off power mode

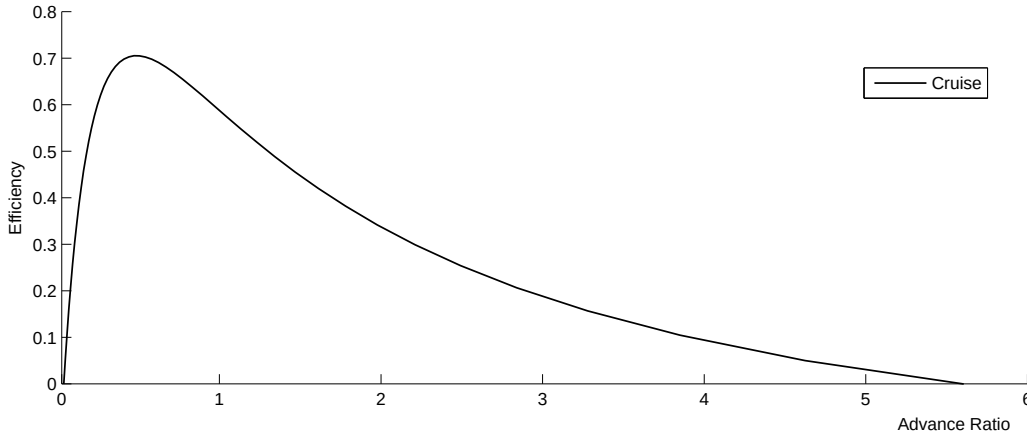


Figure 4.8: Propeller efficiency variation with the advance ratio during the cruise power mode

4.7.2 Mission Power Profile for Long Endurance Mission

As previous sections mentioned, the ISR mission power requirements are varied with the flying modes. Table (4.3) shows the summary of the propulsion power requirements derived in the equations (4.6), (4.15), (4.19) and (4.26). The motor shaft powers during the different flying modes are determined based on the efficiencies obtained in previous section. The most power consuming flying mode is the aircraft take-off power

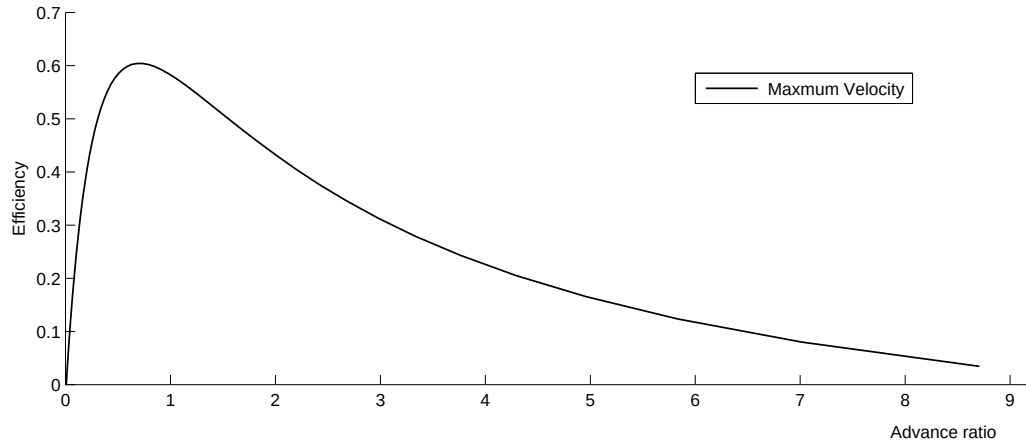


Figure 4.9: Propeller efficiency variation with the advance ratio during the maximum velocity power mode

mode and the lowest consumption is occurred during the endurance mode. The aircraft descend and the landing power requirements are lower than the takeoff and the climb power requirements. Hence, assumes that the landing power is similar to the cruising power.

4.8 Range of the Mission

The range of the aircraft is also an important factor in the aircraft designing process. In some cases, the UAVs are launched for long range missions with the maximum aircraft velocity and ignore the aircraft endurance time. The range of the aircraft is mainly depended on the fuel consumption rate and the operating power of the aircraft [3]. During the long range mission, the aircraft altitude and the flying velocity are maintained at the constant values until the aircraft reaches to the target destination. In this analysis, assumes that the aircraft is flown back with the same velocity and the landing profile is similar to the take-off and climb profiles.

Equation (4.35) shows the relationship between the range of the aircraft R and the fuel consumption rate c [3].

$$R_a = \frac{\eta_{pr}}{c_f} \frac{L}{D} \ln \frac{W_0}{W_1} \quad (4.35)$$

4. UAV PROPULSION POWER REQUIREMENTS

Table 4.3: UAV Power Requirements

Flying modes	Aircraft speed (ms^{-1})	Propeller Power (W)	Propeller Efficiency (η_p)	Shaft power (W)
Take-off power	8.8	223.5	0.84	266
Climb power	8.8	154.2	0.8	154.2
Cruising Power	14.1	60.1	0.71	84.6
Endurance Power	10	40.5	0.76	53.3
Maximum velocity	21.5	150	0.6	250

W_1 is the aircraft weight with the empty fuel tank and W_0 is the aircraft weight before takeoff with fuel. η_{pr} is the propeller efficiency. C_L and C_D are lift and drag coefficient of the aircraft. The specific fuel consumption rate c_f can be described as a function fuel consumption rate ($\dot{w}_f$) and the propeller shaft power P [3].

$$c_f = -\frac{\dot{w}_f}{P} \quad (4.36)$$

The aircraft cruise speed $14ms^{-1}$ is considered for the long range analysis. The shaft power of the propulsion system at this speed is $84.6W$. The PEM fuel cell system hydrogen gas consumption rate is constant at $1.4l/min$ in all conditions. Assuming the hydrogen gas operates in idle conditions, the amount of gas consumed at $60kPa$ pressure and $298K$ temperature is obtained from the ideal gas equation $PV = nRT$ as follows,

$$n_H = \frac{P_r \dot{V}_h}{R_u T_{fc}} \quad (4.37)$$

$$\begin{aligned} n_H &= \frac{60000Pa \times 0.0014m^3/min}{8.314J/Kmol \times 298K} \\ n_H &= 0.0339mol/min \end{aligned} \quad (4.38)$$

Hydrogen gas molar mass $2.0158g/mol$ is substituted into the equation (4.37) and the weight of hydrogen consumed per second is obtained in equation (4.39).

$$\dot{M}_{H_2} = 1.139 \times 10^{-3} \frac{kg}{sec} \quad (4.39)$$

The fuel consumption rate (c_f) at shaft power (P_{shaft}) = $80.1W$ is determined from the 4.40.

$$c_f = -\frac{\dot{w}_f}{P_{shaft}} \quad (4.40)$$

$$c_f = -\frac{1.139 \times 10^{-3} \frac{kg}{sec} \times 9.81ms^{-2}}{80.1W} \quad (4.41)$$

$$c_f = -1.395 \times 10^{-4} m^{-1} \quad (4.42)$$

At level flight operation, the aircraft $\frac{L}{D}$ is equal to $\frac{C_L}{C_D}$. For the $14ms^{-1}$ velocity, C_L and C_D are 0.76 and 0.015 respectively. The aircraft weight with the hydrogen fuel is $71.64N$ and the weight with the empty tank is $71N$. From the equation (4.35), the range of the aircraft is obtained.

$$R_a = \frac{\eta_{pr}}{c_f} \frac{C_L}{C_D} \ln \frac{W_0}{W_1} \quad (4.43)$$

$$\begin{aligned} R_a &= \frac{0.71}{1.39 \times 10^{-4}} \times \frac{0.76}{0.015} \times \ln \left(\frac{71.64N}{71N} \right) \\ R_a &= 2322m \end{aligned} \quad (4.44)$$

Equation (4.44) shows that the aircraft flying at the cruise speed $14ms^{-1}$ can be reached to $2.32km$ range.

The FC-UAV propulsion power requirements and the related performances are used to develop the fuel cell/ battery hybrid power plant which will discuss in chapter.

4. UAV PROPULSION POWER REQUIREMENTS

Electric Propulsion System

Electric propulsion systems are mainly consisted of the electric power sources such as batteries, fuel cells and solar cells and a propulsive electric motor. The hybrid electric power architecture is formed by combining the power sources for one propulsion application. The hybrid electric power system is controlled by power management system in order to direct the hybrid system power flow. In most the fuel cell and the battery hybrid configurations, the fuel cell system operates as the primary power source due to high energy density and the battery is considered as the supplementary power source due to high power density. When the load power is high, both power sources provide the propulsive power and at the low power demand stage, the fuel cell supplies the propulsive power and at the same time charges the battery.

This chapter is mainly focused on the derivations of the power plant and the propulsion system specifications to meet the ISR mission power requirements. The development stages of the PEM fuel cell and the Li-Ion battery hybrid electric system in Matlab Simpower System toolbox and also hardware acquisition for real time emulation will be discussed in this chapter.

5. ELECTRIC PROPULSION SYSTEM

5.1 Electric Propulsion System

The PEM fuel cell and the battery powered hybrid electric configuration is mainly consisted with a PEM fuel cell system, a battery, a DC/DC boost converter, a bidirectional converter and a permanent magnet DC brushless motor with a three phase inverter. The PEM fuel cell system is used as the primary power source and the Li-Ion battery operates as the secondary power source. The DC/DC unidirectional converter boosts up the PEMFC voltage output and regulates the DC bus voltage. The bidirectional converter changes the power flow direction of the battery to charge or discharge while regulating the DC bus voltage. The PMBL DC motor propels the aircraft in all flying conditions. The three phase power inverter converts the DC bus current into the AC current signals and connects to the PMBL DC motor. The motor controller generates the inverter PWM signals based on the hall sensor feedback. Figure (5.1) shows the schematic diagram of the propulsion system.

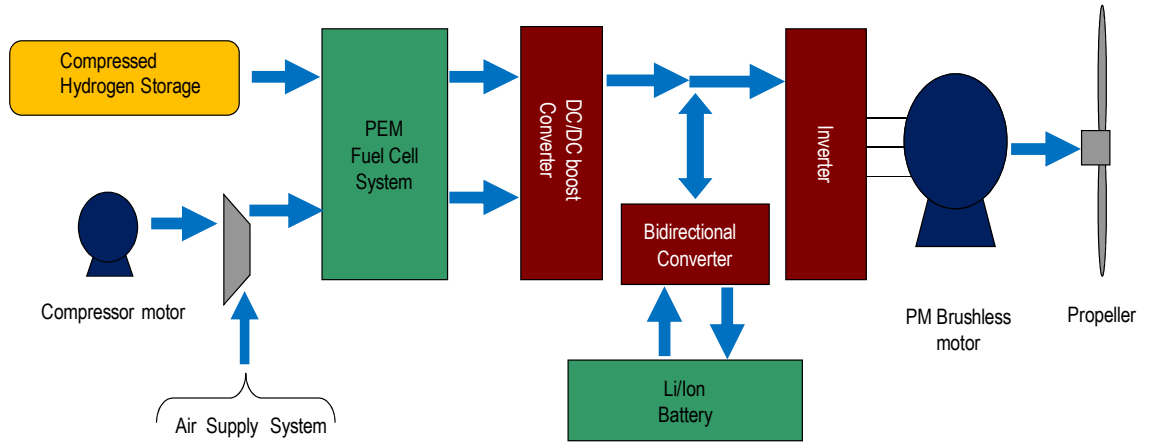


Figure 5.1: Fuel cell and battery hybrid electric propulsion system

5.2 Permanent Magnet Brushless DC motor

The PMBL DC motors are popular among the electric drive systems due to the main advantages such as high power density, high efficiency and the high operational speed [5].

The power consumed by the magnetic excitation of the motor is negligible due to the permanent magnet rotor. The absences of the commutators minimize the friction loss and minimize the motor operational noises. In addition to that, the brushless configuration increases the motor efficiency and reduces the regular maintenance requirement. The PMBL DC motors are relatively compact in size compared with the other types of motors. The motor controller and the inverter are necessary to control the PMBL DC motor. Therefore, the inverter electrical losses reduce the overall efficiency of the propulsion system when it compares with other motors. As the main disadvantage of the PMBL DC motor, the motor can not be controlled during the failure of the inverter and as the results of that the permanent magnets excitation generates a harmful electromotive force in the stator windings [5]. The vast speed range of the PMBL DC motor is the main benefit for the UAV propulsion which requires higher manoeuvrability.

5.2.1 Operational Principals

For the proposed UAV application, the PMBL motor is selected as the propulsion motor drive. The PMBL motor operational principals are analyzed in order to decide the motor specifications. In this section, the fundamentals of the PMBL motors are analyzed and obtained the required performance specifications for the motor.

In the PMBL DC motors, the permanent magnets are located in the rotor and the field windings are positioned in the stator. The hall sensors are used to find the position of the rotor and those sensor signals controls the inverter switching frequency. The DC/AC inverter converts the DC signal into the sinusoidal AC outputs to energize the each stator windings. The MOSFET power switches generates Pulse Width Modulated (PWM) waveforms with the 120° phase lag. Figure (5.2) shows the proposed schematic diagram of the PMBL DC motor.

The interior mounted magnets motors are more suitable than the surface mounted magnet rotor design for high speed applications [5]. For the smooth operation of the motor, the sinusoidal back EMF motor design is selected. For the performance analysis of the BLDC motor, the following assumptions are considered [5]:

- Resistances and inductances of the all the windings are equal and constant
- Motor operating state is not saturated

5. ELECTRIC PROPULSION SYSTEM

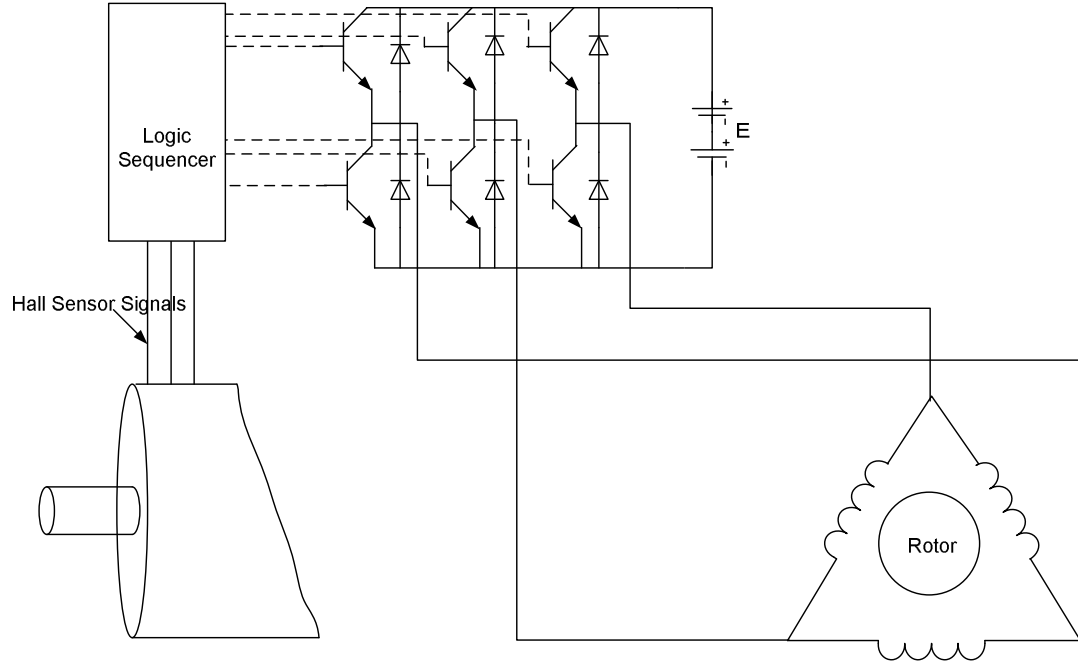


Figure 5.2: Permanent magnet brushless DC motor and the three phase inverter

- Iron losses are negligible
- MOSFET switches are in ideal conditions

Figure (5.3) shows the simplified equivalent circuit for one phase of the motor. The motor mechanical power output P_{me} can be represented as shown in (5.1).

$$P_{me} = m|E||I| \quad (5.1)$$

$$P_{me} = m\omega|\lambda_m||I| \quad (5.2)$$

m is the number of phases and ω is the motor rotational speed. λ_m represent the Phasors with rms amplitudes. I is the phase current of the motor. The torque induced T_e by the motor can be shown as in (5.3).

$$T_e = \frac{P_{me}}{\omega_r} \quad (5.3)$$

$$T_e = \frac{m\omega|\lambda_m||I|}{\omega_r} \quad (5.4)$$

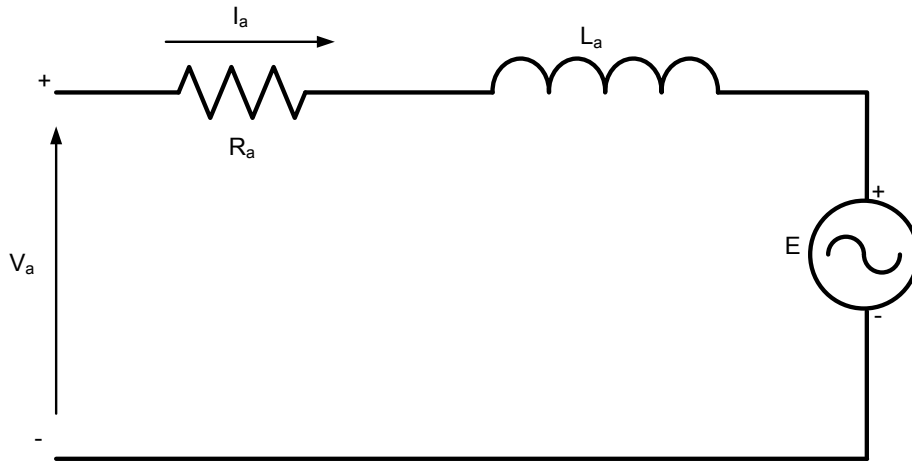


Figure 5.3: Equivalent circuit of the motor

ω_r is the rotor speed in rad/s where, $\omega_r = \frac{2\omega}{p}$. p is the number of poles of the motor. From the equations (5.1) and (5.3), the motor induced torque can be represented as shown in (5.5).

$$T_e = \frac{mp}{2} \lambda_m I \quad (5.5)$$

The back EMF of the motor E is proportional to the rotor angular velocity (ω) as shown in (5.6).

$$E = \frac{p}{2} \lambda_m \omega_r \quad (5.6)$$

By applying the Kirchhoff's law, the following motor equation can be obtained,

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + E \quad (5.7)$$

V_a is the supply voltage for phase A, R_a is the winding resistance, L_a is the inductance of the motor windings. Assuming that $\omega L_a \ll R$, from the equations (5.5), (5.6), and (5.7), the relationship between the induced torque and the rotor speed can be expressed

5. ELECTRIC PROPULSION SYSTEM

as shown in (5.9),

$$V_a = \frac{2R_a}{mp\lambda_m}T_e + \frac{p}{2}\lambda_m\omega_r \quad (5.8)$$

$$\omega_r = \frac{V_a}{p\lambda_m/2} - \frac{R_a}{m(p\lambda_m/2)^2}T_e \quad (5.9)$$

By defining the back EMF constant $k_e = \frac{p}{2}\lambda_m$ and the torque constant $k_t = \frac{2}{mp}\lambda_m$, the motor torque and the speed relationship can be simplified as shown in (5.10)

$$T_e = \frac{(V_a - K_e\omega)k_t}{R_a} \quad (5.10)$$

The figure (5.4) shows the speed and the torque relationship at constant voltage based on the equation formulated in (5.9).

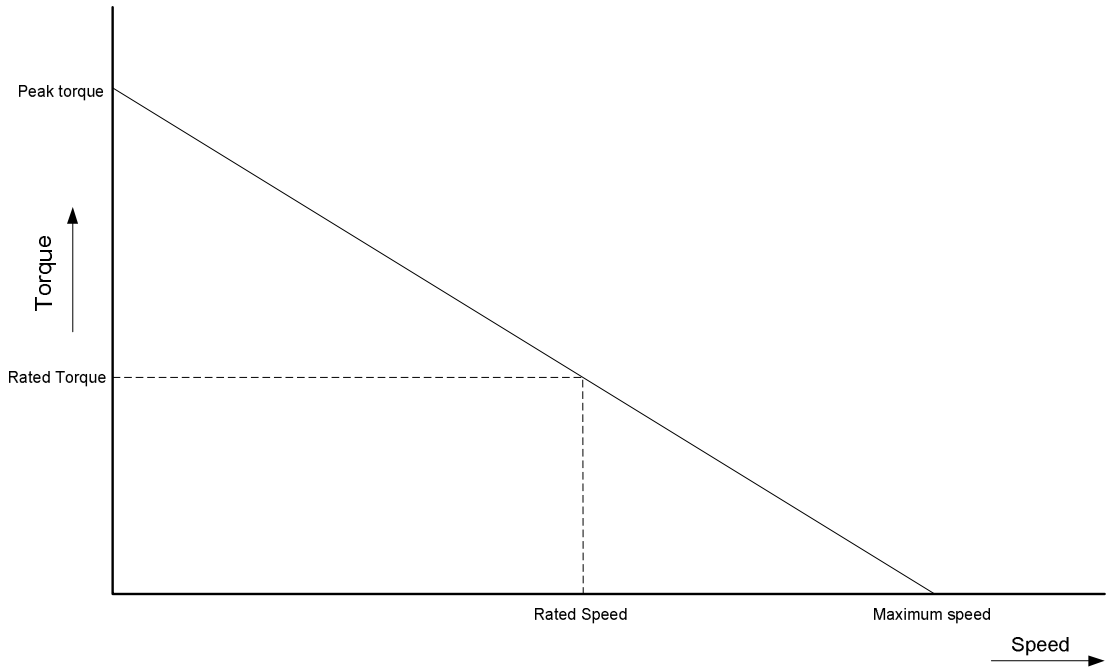


Figure 5.4: *Torque vs Speed curve*

In electric propulsion system, the induced torque should follow the desired load torque generated by the motor controller. The load torque T_L and the induced torque (T_e)

relationship is shown in (5.11) [5].

$$T_e = T_L + J \frac{d\omega}{dt} + B\omega \quad (5.11)$$

J is the motor shaft inertia coefficient and the B is the viscous friction coefficient [5].

5.2.2 Motor Control Approach

In most traction applications, the brushless DC motor controller is consisted with a speed controller and a current controller to control the motor performances. The speed controller is used to compare the referenced speed (ω_{ref}) value which is the desired speed of motor with the actual speed of the motor (ω). The angular velocities which were determined in chapter (4) in section (7) are used as the referenced velocities to generate the required thrust for the aircraft. Table (5.1) shows the required angular velocities of the motor in different flying conditions.

Table 5.1: *Motor angular velocities*

Flying mode	Reference angular velocity (rpm)
Take-off	1867.4
Climb	2445
Cruise	3183
Endurance	3395
Maximum velocity	4277

A PI controller is used to regulate the actual speed of the motor. The speed controller produces the referenced torque signal for the current controller based on the motor speed and torque relationship. The current controller generates the required PWM pulses based on the reference torque signal of the speed controller, the hall sensors feed-back and the phase currents feedback. The schematic diagram of the motor controller is shown in figure (5.5). The simulation models of the motor and the motor controller are shown in figure (5.6).

5. ELECTRIC PROPULSION SYSTEM

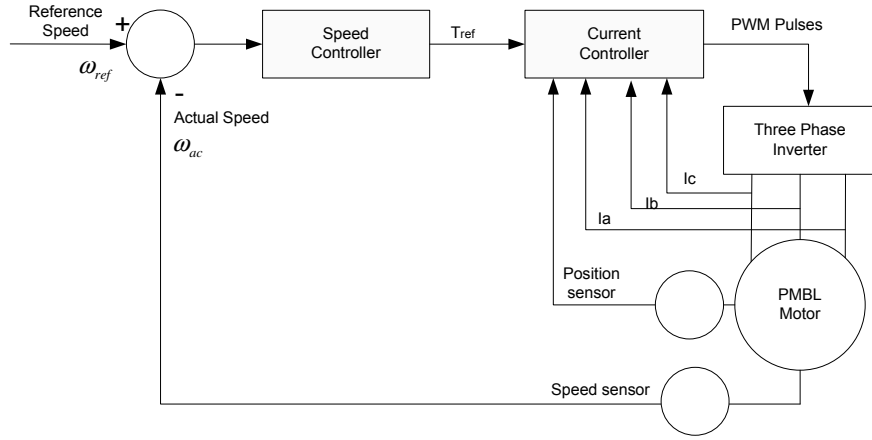


Figure 5.5: PMBL DC motor control architecture

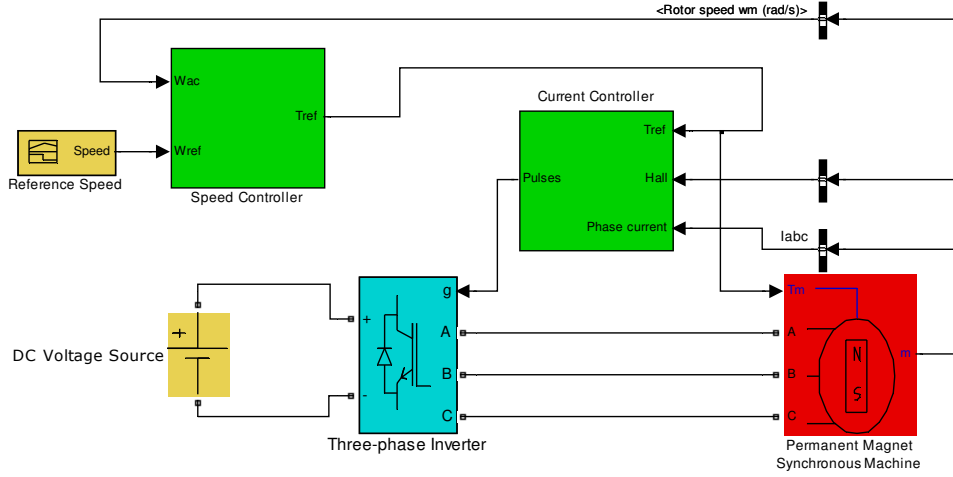


Figure 5.6: The simulation models of the PMBL DC motor and controllers

The gate signals generated by the current controller are used to control the three phase inverter. Three phase inverter is consisted with six MOSFET switches and connects to the motor phases. Figure (5.7) and (5.8) show the developed simulation models of the speed controller and the current controller. The speed controller integral ($k_i=0.0776$) and proportional ($k_p=0.0332$) gains are determined by considering the rotor inertia, pole and the friction factor. The desired response time is 0.13 seconds. The torque reference signal is generated as the output signal of the speed controller. The current controller which is shown in figure (5.8) is consisted with hall sensor signals decoder, current regulator and a pulse generator. The decoder is used to generate the logical sequences for the changes in the each phase. Based on the hall sensors feed back, the

reference current is generated and regulated with the actual phase current in current regulator block. The current regulator consists with PI controllers and produces gate signals for the PWM signal generator. Based on the gate signals, the PWM signals change their duty ratio to control the current flow of the each phase and hence control the speed of the motor. In the simulation, the propeller load is applied as the load torque (τ_m) to the motor. The load torque is determined based on the required motor shaft power and the rotor speed.

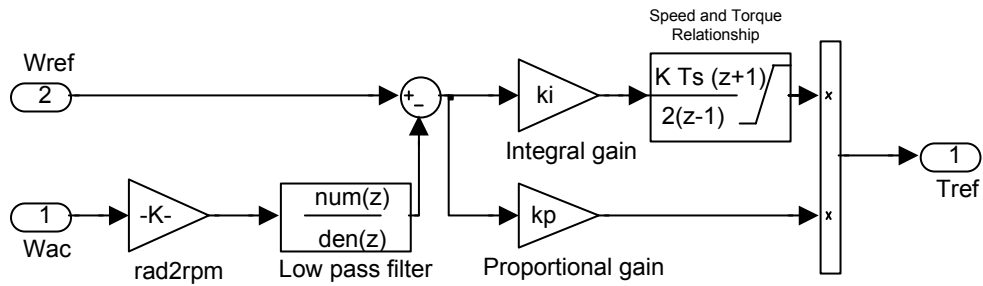


Figure 5.7: Motor speed controller

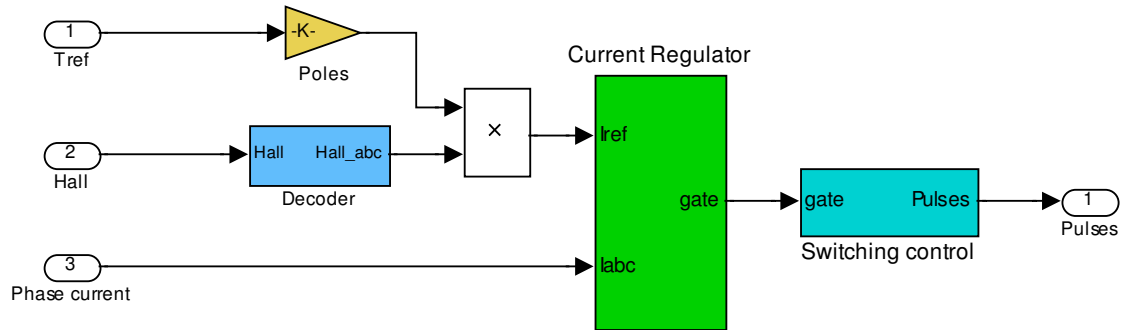


Figure 5.8: Motor current controller

5.2.3 Motor Specifications

The motor specifications are determined based on the propulsion power requirement of the UAV. The peak power demand is appeared during the take-off and the maximum rate of climb of the aircraft. The propulsion system and the power plant are operated

5. ELECTRIC PROPULSION SYSTEM

below the rated power during the cruising and the endurance modes. The motor and the motor controller specifications are determined to meet the each flying mode power requirement.

The commercially available a PMBL motor and a motor controller specifications are considered for the simulation models of the propulsion motor and the controller. A Cruzet PMBL motor (model no:80190502) which has delta connected windings and A Microchip motor controller (model no :DN485680) which are shown in figure (5.9) specifications are selected to model the motor and the controller. The specifications shown in table (5.2) are used to develop the simulation motor model.

Table 5.2: *Motor Specifications*

Max. speed (<i>rpm</i>)	8000
Torque peak in (<i>mNm</i>)	1160
Maximum continuous torque (<i>mNm</i>)	463
Motor constant ($mNm/W^{\frac{1}{2}}$)	103
Rotor inertia (<i>gcm²</i>)	230
Number of phases (<i>delta config</i>)	3
Number of poles	4
Phase-to-phase resistance (Ω)	0.25
Torque constant (<i>mN.m/A</i>)	50.4
Back EMF constant (<i>V/(rad/s)</i>)	0.0504
Inductance (<i>mH</i>)	0.59

5.3 DC Bus Power

The hybrid electric power plant which consists of a PEM fuel cell and a Li-Ion battery is designed to respond the peak power requirements during the takeoff, the climb and the maximum velocity. The take off power mode is the highest power consuming flying mode compared to the other flying modes which are shown in table (4.3). In the electric propulsion system, the deficiencies of the propeller, the propulsion motor and

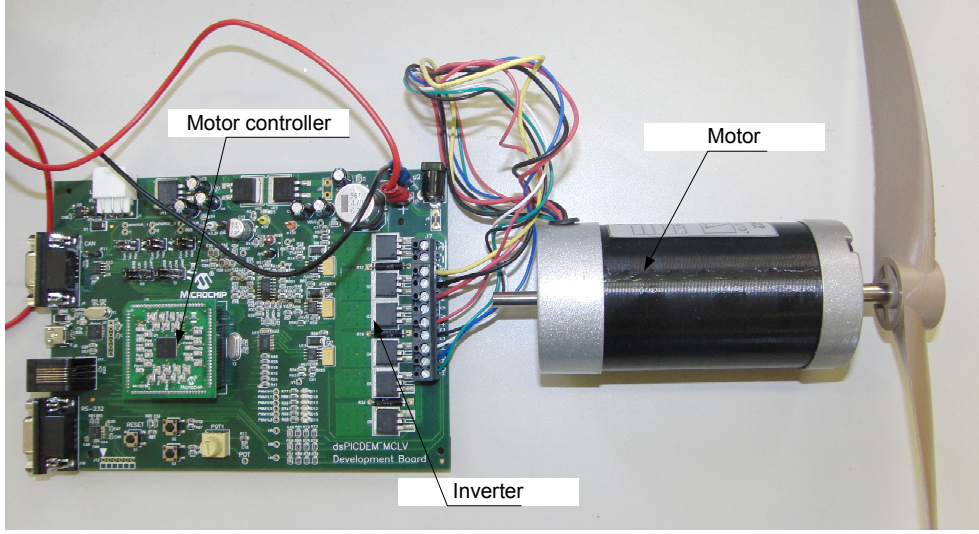


Figure 5.9: PMBL DC motor and inverter drive

the power converters reduce the power available for the thrust. The propeller efficiencies in different flying modes were determined in chapter (4.7). From the manufacturer hand book, the PMBL DC motor efficiency is $\eta_m = 0.9$. The three phase inverter has $\eta_{inv} = 0.88$ efficiency. Assumes that the aircraft sensors, communication devices and the PEMFC system BOP are consumed constant 15W power during the mission.

P_{shaft} is shaft power generated by the PMBL DC motor. The motor shaft power output P_{shaft} is reduced by the internal losses caused by motor windings. The relationship between the motor shaft power and the power input to the motor is shown in (5.12).

$$P_{shaft} = \eta_m P_{inv} \quad (5.12)$$

η_m is the motor efficiency and the P_{inv} is the power output of the three phase inverter. P_{inv} is a function of the DC bus voltage $V_{DC_{bus}}$ and the DC current $I_{DC_{bus}}$ as shown in (5.13).

$$P_{inv} = \eta_{inv} V_{DC_{bus}} I_{DC_{bus}} \quad (5.13)$$

η_{inv} is the inverter efficiency. By combining (5.12) and (5.13), the required DC bus power

5. ELECTRIC PROPULSION SYSTEM

is obtained in (5.14).

$$P_{DC} = \frac{P_{shaft}}{\eta_m \eta_{inv}} \quad (5.14)$$

By substituting the motor shaft power requirements to the equation (5.14), the DC bus power for the each flying mode is obtain as shown in table (5.3). This includes the 15W payload power. In order to share this DC bus power between the PEMFC system and the battery, the voltage and the current limits are defined in the hybrid power plant designing process. Based on these limits, the suitable fuel cell system and battery are selected.

Table 5.3: DC bus power at different flying modes

Flying modes	DC bus Power (W)
Take-off power	355
Maximum rate of climb power	213.6
Cruising Power	125
Endurance Power	86.2
Maximum velocity	334.6

5.4 Battery Systems

In the hybrid configuration, the battery operates as a supplementary power source when the load power demand is higher than the fuel cell power. During the high power flying modes of the aircraft such as the take-off, the climb and the maximum velocity modes, the battery supplies the additional power while the PEM fuel cell system operates at efficient power level. In addition, the battery is used to respond the transient load current changes. The PEM fuel cell system shows the capacitive response due to the charge accumulations closed to the electrodes. The delay in transient response can be eliminated by introducing the battery as the secondary power source.

The battery stores energy as the chemical energy and converts into the electric energy during the discharging. The major types of battery technologies that are mostly used in automobile industry are Lead acid batteries, Nickel based batteries and Li-Ion based batteries. Table (5.4) shows the comparison of different types of battery technologies used in electric vehicles to identify the suitable battery system for UAV propulsion system [5]. The lead acid batteries are the most popular batteries in automobile applications due to the low cost of the materials such as lead, sulphuric acid. The lead acid battery major draw back is the low energy density [5]. The Nickel based batteries are relatively lighter than the Lead acid batteries [5]. The Nickel based batteries have high power density compared to the Lead acid batteries but has higher self discharging rate [5]. However, the manufacturing cost of the Nickel based batteries is relatively high. The Li based batteries are the most promising battery technology for the electric vehicle applications in automotive and aerial domain. The main Lithium based batteries are Li-polymer, Lithium sulfur and Li-ion batteries. The main advantage of the Li-polymer battery is the solid polymer electrolyte, which reduces the reaction activity with the Li and leads to a safe operation as well as increases the battery compactness [5]. In addition to that the Li-polymer battery has the highest specific power density 315W/kg [5]. The main disadvantageous of the Li-polymer battery is weak performance in low temperature due to the temperature dependence of the ionic conductivity and high manufacturing cost for the thin polymer layer.

Lithium sulphur dioxide (Li/SO_2) battery is an another battery solution for the vehicles which need high current and high power requirements. The Li/SO_2 shows robust performances in low temperature compared to the other Lithium batteries. These batteries are mostly used in military applications due to the high energy density which an important requirement for certain missions [71].

The Li-ion battery systems are introduced to the market as the low cost, high specific power and high specific energy device by overtaking the market dominant Nickel Metal hydride (NiMH) batteries. The Li-Ion batteries are widely used in electric vehicles and hybrid electric vehicles due to the low cost associate with the battery manufacturing process. These batteries are used as a reliable battery solution in the most of the electric vehicles developed by the pioneering manufacturers such as Toyota, Nissan and Honda. In the automobile sector, the most researches have been carried out to

5. ELECTRIC PROPULSION SYSTEM

develop the fast charging methodologies for the Li-Ion batteries and show significant improvements in the battery charging time [72].

The cost associate with the battery system is also important for mass scale production for commercial purposes. At this stage, the investigation on the FC-UAV propulsion system is for the scientific developments. In the battery selection process, the author considered not only the battery performances but also the commercial advantages of the Li-Ion battery compared to the Li-polymer and Li/SO₂ batteries.

Table 5.4: Battery types and performance specifications [5]

Battery type	Specific Energy (Wh/kg)	Specific Power (W/kg)	Efficiency (%)
Lead Acid	35-50	150- 400	> 80
Nickel/cadmium	5060	80150	75
NimH	70-95	200-300	70
Li-Ion	80-130	200-300	> 95
Li-Polymer	130-200	315	> 90

5.4.1 Battery Characteristics

The Li-Ion battery state of charge (SoC) is an important parameter to determine the charge capacity relative to the fully charge capacity. When the battery is fully charged, the battery SoC is maximized and the minimum SoC is occurred at the battery cut-off voltage. Most commonly, the battery SoC is expressed as shown in (5.15) [5].

$$SoC = SoC_0 - \int \frac{idt}{Q(i)} \quad (5.15)$$

SoC_0 is the initial value of the battery SoC . Figure (5.10) shows the equivalent circuit diagram of the battery cell. The battery internal resistance is varied with the battery

electrochemical reaction rate. Therefore, the battery charging and the discharging characteristics differ from each other due to the internal resistance changes in each process. Figure (5.11) shows the characteristics curves of the battery during the discharging processes. For this analysis, the battery cut-off voltage is considered as 10V. However, due to the impossibility of the measuring battery SoC during operation, it has been assumed that the battery terminal voltage is proportional to the battery SoC as shown in figure (5.11).

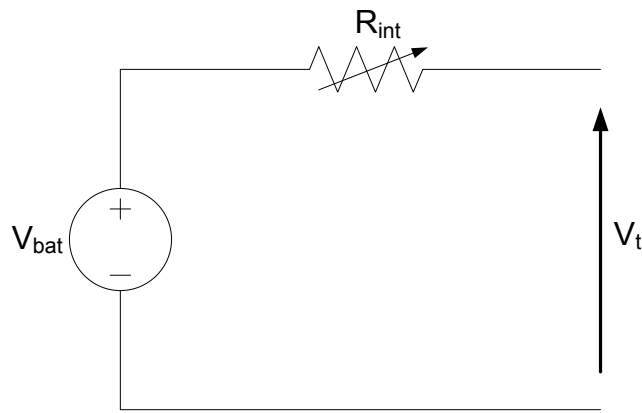


Figure 5.10: *Equivalent circuit of the battery cell*

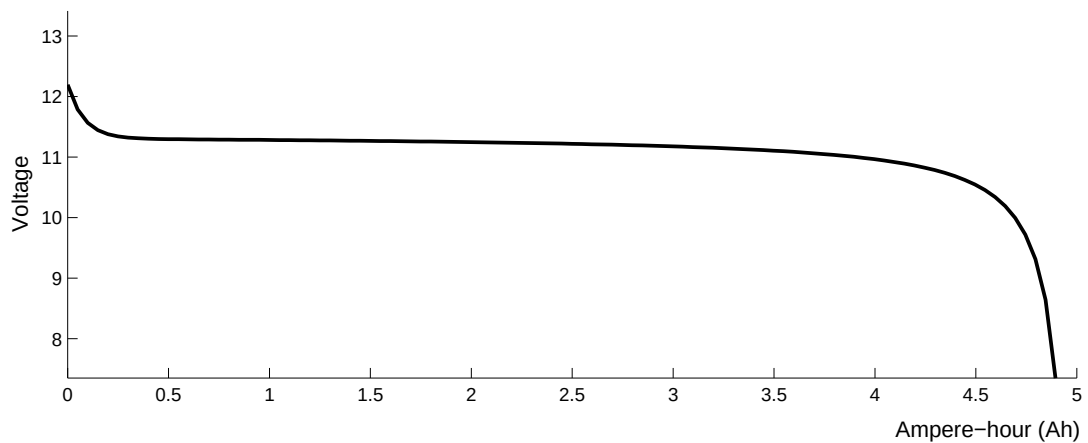


Figure 5.11: *Discharging curve of the battery*

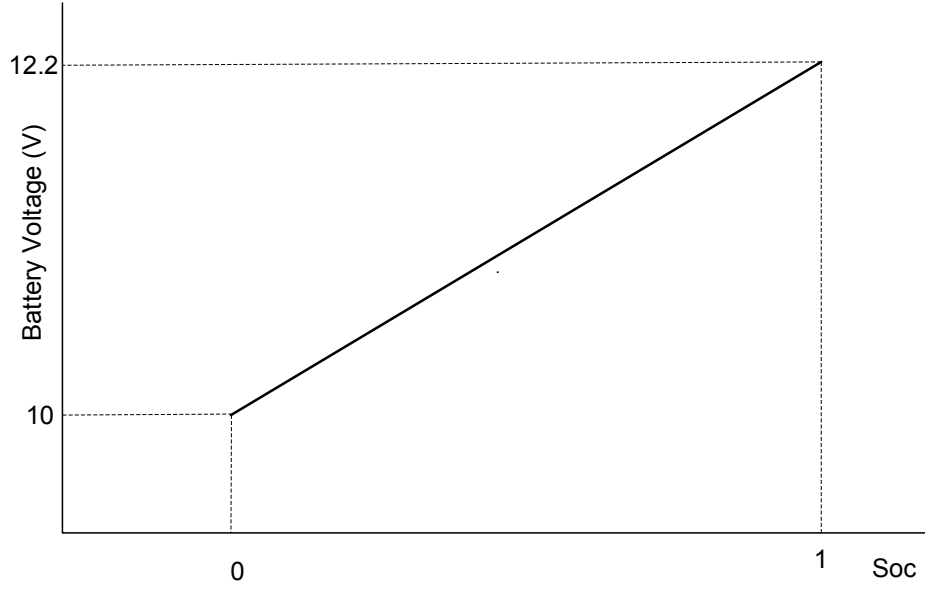


Figure 5.12: Battery SoC vs terminal voltage

5.4.2 Battery Sizing

In the hybrid electric power configuration, the battery capacity C_B is obtained from the selection process of the bidirectional converter. The proposed hybrid power system has 24V DC bus voltage and the bidirectional converter input voltage is varied between 10V and the 13V as the design consideration. Hence, 12V Li-Ion battery is selected as the supplementary power source. The required battery capacity is determined at the battery minimum voltage which represents the battery lowest energy capacity. Equation (5.16) shows the relationship between the battery capacity and the battery voltage at a certain power condition. Due the battery sizing constraints such as size and weight of the battery, the selection of the battery power capacity is based on the endurance power which operates longer period in low current state. Therefore, the DC bus power (P_{DC}) at cruise mode is 86.2W which is shown in table (5.3) is considered for the battery sizing process. The bidirectional power converter efficiency is 0.88 and the battery minimum voltage is 10V. In most of the automobile batteries, the maximum discharging current is limited $(0.5 - 0.7)C_B$ to prevent the damages caused by the high current [35]. By considering the maximum discharging rate, 0.7 is selected for the sizing process. From the equation (5.16), the battery capacity is determined as 14Ah.

$$C_B = \frac{P_{DC}}{0.7 \cdot \eta_{BDC} \cdot V_{batmin}} \quad (5.16)$$

$$C_B = \frac{86.2W}{0.7 \times 0.88 \times 10V} \quad (5.17)$$

$$C_B = 14Ah \quad (5.18)$$

In the hybrid electric configuration, the bidirectional converter controls the current flow of the battery. The battery charging and discharging current limits are depended on the boost mode and buck mode operations of the bidirectional converters. In the buck mode operation of the bidirectional converter, the Low Voltage (LV) side voltage output is defined as the rated battery voltage (V_{bat}) = 12.2V . The charging current of the battery is considered as the $0.1C_B$ by the most developers [35]. Therefore, the battery charging current limit is obtained from the equation (5.19).

$$I_{chg} = 0.1 \times C_B \quad (5.19)$$

$$I_{chg} = 0.1 \times 14 \quad (5.20)$$

$$I_{chg} = 1.4A \quad (5.21)$$

During the boost mode operation of the bidirectional converter, the battery supplies the propulsion power. When the battery charge is low, the terminal voltage of the battery reduced to minimum $V_{batmin} = 10V$. The maximum current can be drawn from the battery during the take-off mode operation is determined in the equation (5.22).

$$I_{batmax} = \frac{P_{cr}}{\eta_{BDC} V_{batmin}} \quad (5.22)$$

$$I_{batmax} = \frac{355W - 125W}{0.88 \times 10V} \quad (5.23)$$

$$I_{batmax} = 26A \quad (5.24)$$

From the table (5.4), the Li-Ion battery specific energy is selected as average value 110Wh/kg. For the battery which has 14Ah battery capacity and 12V voltage, the

5. ELECTRIC PROPULSION SYSTEM

Table 5.5: *Battery specifications*

Parameter	Value
Fully charge voltage	12.2V
Minimum voltage	10 V
Rated Capacity	14Ah
Charging Voltage	13.3 V
Internal resistance	0.021 Ω
Nominal Discharge Current	2.17A
Dimensions (<i>mm</i>)	161 $\times$ 115 $\times$ 56
Weight	950 g

weight of the battery can be obtained as 1.5kg . The commercially available Li-Ion battery which is developed by Tracerpower (model no : BP2546) [73] has the similar specifications such as 14Ah battery capacity and 12V voltage with 0.95kg weight. The selected Li-ion battery specifications are shown in table (5.5). The weight of the Lead acid battery which has similar specifications is approximately 3.5kg . Therefore, significant weight reduction can be achieved in the hybrid electric system by using the Li-Ion battery compared to the Lead acid battery.

5.5 Power Converters

The power converters regulate the voltage and the current outputs and share the load power between the battery and the PEMFC system. The proposed hybrid electric system consists of an unidirectional converter for the fuel cell and a bidirectional converter for the battery. In the literature, the common advantageous of the regulated power architecture over the unregulated architecture were discussed and the benefits of the regulated hybrid electric system were identified. In most fuel cell applications, the fuel cell system is connected to the unidirectional converter to regulate power output. However,

the battery can be connected to the DC bus with or without the bidirectional converter. There are some advantages in the regulated architecture which has bidirectional converter connected to the battery over the unregulated architecture which has the battery directly connected to the DC bus.

As the main advantage of the bidirectional converter, the battery power rating, size and weight can be reduced. In addition, the fuel power rating can be decreased based on the battery selection. Furthermore, the bidirectional converter can operate in buck mode to charge the battery. In the buck mode operation, the battery can be charged in constant current or constant voltage modes. Therefore, the battery life time can be improved by controlling the discharging and charging sequences.

By connecting the battery directly into the DC bus, a controlled power distribution would not be achieved. In unregulated battery configuration, If the load demand is high, the fuel cell systems power output can be regulated and the balance of the power can be drawn from the battery without control. However, if the unidirectional converter operates in the voltage control mode by regulating the DC bus voltage at 24V, the battery start to charge when its terminal voltage is lower than the 24V even load demand is high. If the unidirectional converter regulates the fuel cell current, the DC bus voltage will be the terminal voltage of the battery. When the battery charge is depleting the DC bus voltage also reduced. In this situation, the fuel cell current will be increased and the fuel cell consumes more hydrogen gas and auxiliary power. Therefore, the battery capacity should be high in unregulated architecture and hence battery size and weight also increased. The absence of the bidirectional converter, the hybrid electric system will be bulky than the regulated system.

For the load power sharing process, the power management algorithm is developed to control the power flow of the fuel cell system and the battery. The unidirectional converter operates as a boost converter for the fuel cell system. The bidirectional converter distributes the load current between the battery and the fuel cell system when it operates in boost mode. On the other hand, if the BDC operates in buck mode, the PEM fuel cell system power is used to charge the battery and supplies the propulsion power. The BDC operating mode which is the buck or the boost is depended on the UAV power requirement. For the each flying condition, the motor current is changed to achieve desired angular velocity. For an example, when the FC-UAV is changed from the maximum climb mode to the cruising mode, the DC bus current is varied from 8.9A to 5.2A

5. ELECTRIC PROPULSION SYSTEM

and generates the required angular velocity. Table (5.6) shows the DC bus currents at 24V DC bus voltage for each flying mode.

Table 5.6: DC bus currents at the different flying modes

Flying modes	Current (A)
Take-off mode	14.8
Maximum rate of climb mode	8.9
Cruising mode	5.2
Endurance mode	3.6
Maximum velocity mode	13.9

The amount of the load current shared with the battery and the FC system is decided by the power management system. The decisions taken by the power management system are implemented by the voltage and current mode controllers of the power management system. Based on the load current, the power management system generates the required PWM signals for the UDC and the BDC to decide the amount of load current needs to be shared between the power sources. In order to decide the BDC operating mode whether buck mode or boost mode, the boundary condition is defined $I_{dc} > 5.3A$. When the load current is greater than 5.3A, the BDC is operated as the boost converter. Hence, as can be seen from the table (5.6), the BDC moves to the buck mode during the endurance and cruising power mode due to the low DC bus current.

The maximum UDC current is limited 5.3A which is just above the cruising mode maximum power. For the take-off, the climb and the maximum velocity modes, the load currents are greater than the 5.3A. The PEM fuel cell system operating power which is high power or below the rated power is depended on the propulsion power demand. The BDC is operated in the boost mode to supply the balance of the power during the high load power. When the load current is less than 5.3A, the BDC is switched to the buck mode and charges the battery.

The UDC and the BDC converters models developed in the Matlab Simpower System are shown in figures (5.13) and (5.14). These converters parameters such as inductance, capacitance and switching frequencies will be derived in chapter (8) as the part of the

converter designing process. Those parameter values are used in the Simpower system models and the simulations.

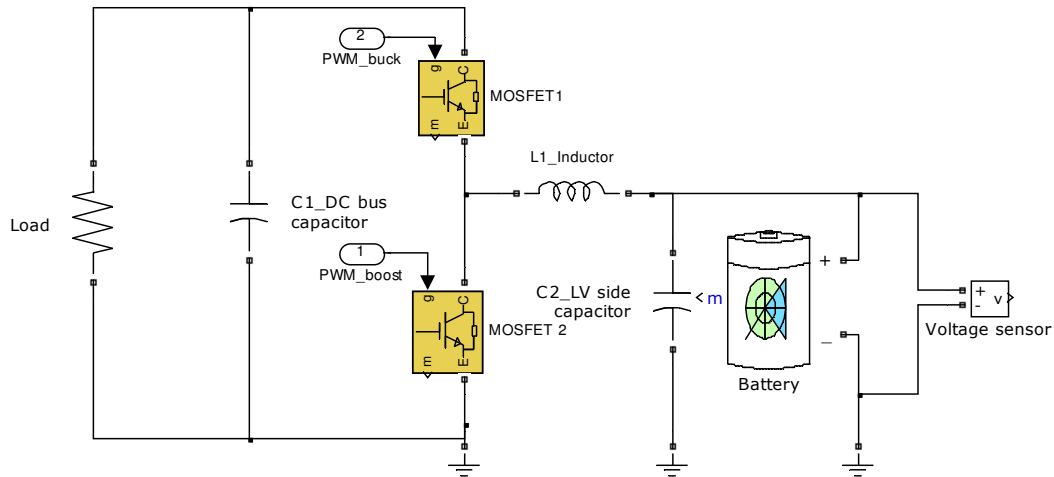


Figure 5.13: Bidirectional converter developed in the Matlab Simpower System

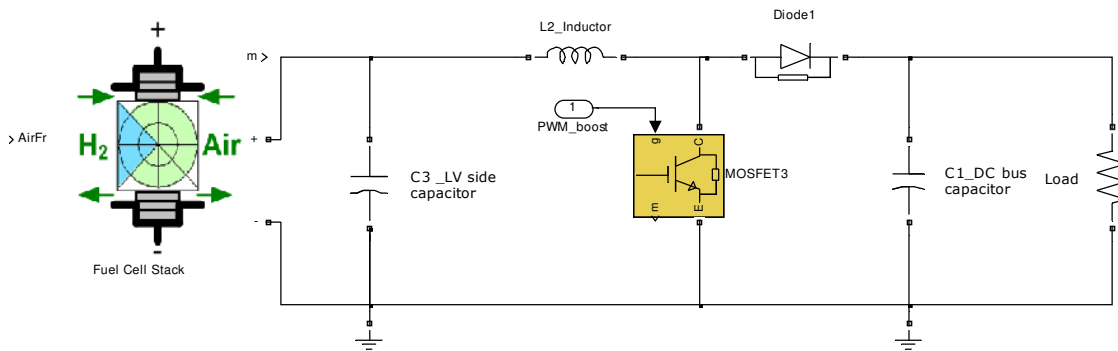


Figure 5.14: Unidirectional converter developed in the Matlab Simpower System

The proposed unidirectional and the bidirectional converters are designed with an embedded control system as the implementation framework of the research. Chapter (8) will discuss the design process of the power converters and testified results will be illustrated in chapter (9).

5. ELECTRIC PROPULSION SYSTEM

5.6 PEM Fuel Cell System

The PEM fuel cell system is operated as the primary power source of the hybrid system. As the main power supply unit, the fuel cell system generates the electricity continuously throughout the mission. The PEM fuel cell system maximum power is limited to the 150W. In order to provide the cruising power 125W and the endurance power 86W, commercially available a Horizon H-100 PEM fuel cell system which is shown in figure (5.15) is selected [69]. Initially, the PEM fuel cell system is modelled in Matlab Simpower toolbox similar to the Horizon H-100 fuel cell.

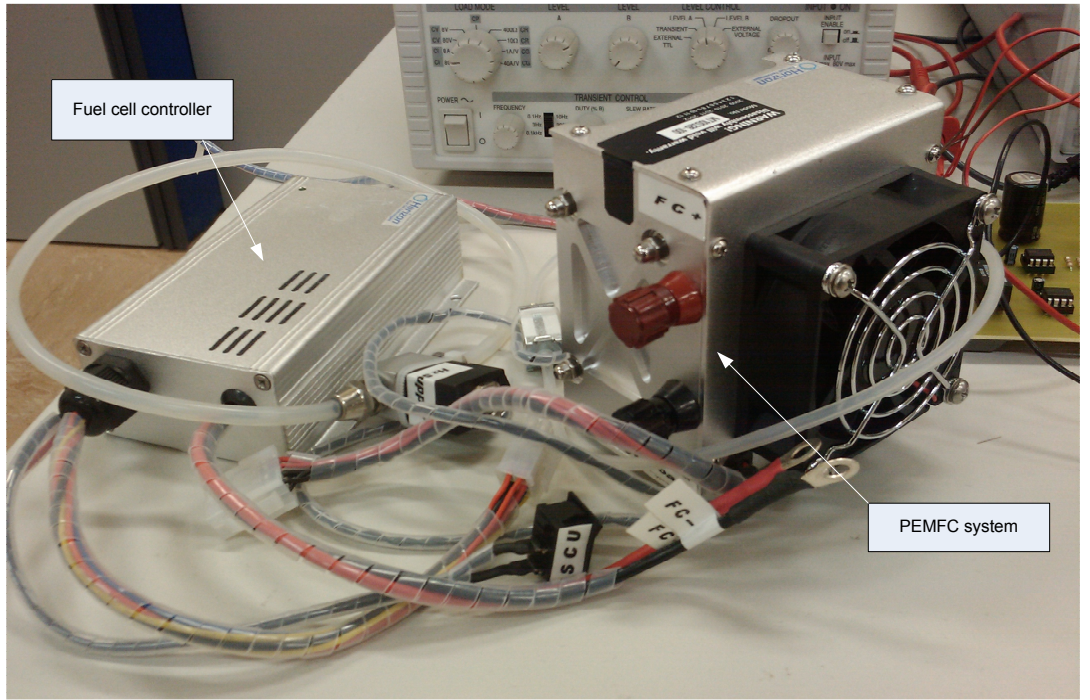


Figure 5.15: Horizon H-100 PEMFC system and controller

The Horizon H-100 PEM fuel cell system specifications are shown in table (5.7) [69]. The fuel cell system rated voltage and current are 14V and 7.2A and has 24 cells. The fuel cell system input voltage is ranged between 13V and 23V. The PEM fuel cell system requires 1.4l/min hydrogen flow rate and the supply hydrogen pressure should be 0.4bar – 0.6bar. The fuel cell system efficiency is 40% at the rated power. Figure (5.16) shows the PEM fuel cell system operating power variations with the current.

Table 5.7: *Simpower System PEM fuel cell system specifications*

Number of cells	24
Rated power	100W
Maximum power	150W
Rated voltage	14V
Rated current	7.2A
Output voltage range	13V-23V
Weight	0.95kg
Rated H_2 gas consumption	1.4l/min
Hydrogen pressure	0.4-0.6Bar
Max stack temperature	65 ⁰ C
Hydrogen purity	99.999%
Efficiency of system	40% @14V

5.7 Simulation Models

Matlab Simpower system tool box is used to design the hybrid electric system in simulation environment. The parameters of the fuel cell system, the battery and the brushless motor which are discussed in the previous sections are used in Simpower system models. The unidirectional and the bidirectional power converters inductance and capacitance which are obtained from the chapter (8) are included to the Simpower system power converters models.

The research objective is mainly rely on the development of the power management system to operate in supervisory control level. The author used the hybrid electric system developed in Simpower system tool box as the real time representation of the hybrid electric system. The Simpower system models current flows and the voltage variations were same as the actual system and the fuel cell, battery and the motor characteristics were similar to the real components discuss in the previous sections. The

5. ELECTRIC PROPULSION SYSTEM

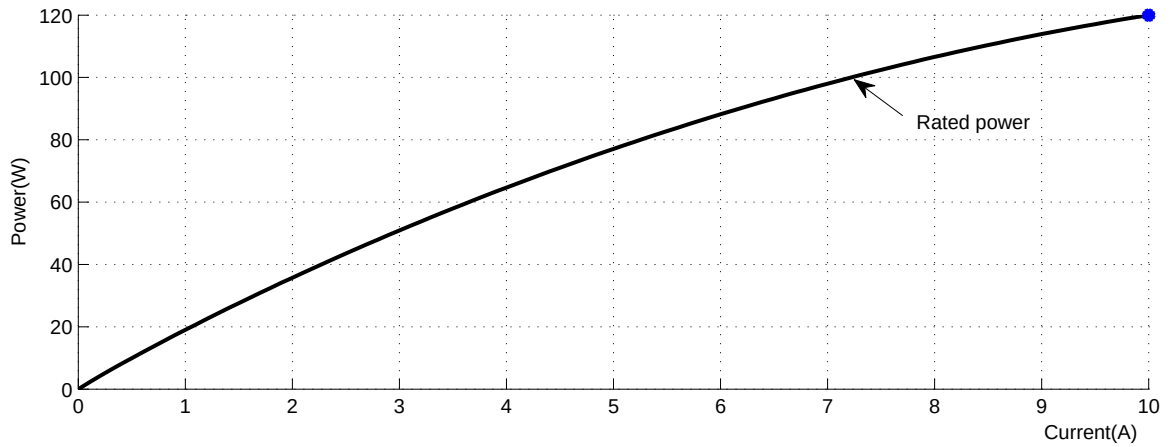


Figure 5.16: PEM fuel cell power variation with current

hybrid system developed in the Simpower system tool box approximately represents the real time system. Finally, the performances of the power management system are verified by comparing the results obtained from the Simpower system hybrid electric propulsion system and the actual hardware setup.

The hybrid electric propulsion system developed in Matlab Simpower system toolbox as shown in figure (5.17). The results obtained from the simulations will be discussed in chapter (6).

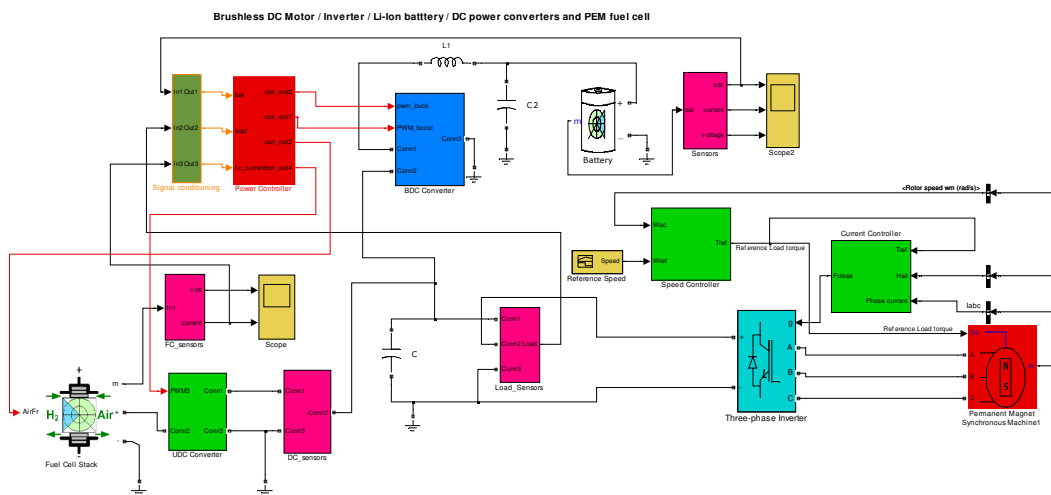


Figure 5.17: Hybrid power system developed in Matlab Simpower System toolbox

Intelligent Power Management

6.1 Introduction

The power management (PM) is an essential concept in the fuel cell and the battery powered propulsion system in order to distribute the load power between the two power sources. The power management is a decision making process which is trying to meet the load power demand with available power while optimizing the hybrid system energy usage. In most hybrid power configurations, the power management system pursues a vital role in power sources utilization. The modern power management systems are consisted with an embedded controller and a power electronic interface to implement the power management decisions. In the first part of the hybrid system power management, a power management algorithm is introduced to share the load power. The feedbacks which are gained from the battery and the load current are used to decide the amount of power taken from each power source. The power management system generates the appropriate Pulse Width Modulated (PWM) signals for the power converters. The UDC controls the PEM fuel cell system current at desired level while allowing the battery to provide the balance of the power through the BDC. At the second stage of the power management, a fuel cell air supply system control architecture

is introduced to achieve maximum net power output from the fuel cell system. Based on the amount of current shared with the PEM fuel cell system, the air supply system controller optimizes the air compressor performances.

In the first section of this chapter, the power management algorithm and its implementation framework will be discussed. In the later part of the chapter, the simulation results will be used to verify the proposed algorithm and the control architecture.

6.2 Power Management System

The power sources hybridization process can be implemented as unregulated and regulated hybrid power architectures. In the unregulated power architecture, the fuel cell system and the battery are directly connected to the DC bus without controlling the power flow. Therefore, the DC bus voltage varies with the load current changes. When the load current is drawn for a longer period, the battery depletes and the terminal voltage of the battery will be reduced. In order to respond to the battery power loss, the fuel cell current is increased and at the same time the fuel cell terminal voltage is reduced to the battery voltage. In the unregulated hybrid system, the fuel cell system is operated below the maximum power capabilities throughout the mission. The unregulated architecture main advantages are simpler design, higher efficiency and minimal cooling requirement than the regulated system. The main drawback of the unregulated hybrid system is the uncontrollability of the current flow.

In the regulated power architecture, the bus voltage is maintained at a constant level and the current flow is controlled by varying the UDC and the BDC PWM signals. For an example, while the UDC HV side is maintained at 24V and the BDC voltage output is increased greater than 24V, then the fuel cell system current is lowered and the battery starts to contribute more power than the previously held. Therefore, the regulated hybrid system has advantages over the unregulated system in terms of current flow controllability. In addition to that, by using the bidirectional converter, the battery can be charged when the load demand is low. However, the regulated architecture components such as the UDC and the BDC add an extra weight to the overall system and the converters losses reduce the system energy efficiency. In the regulated hybrid

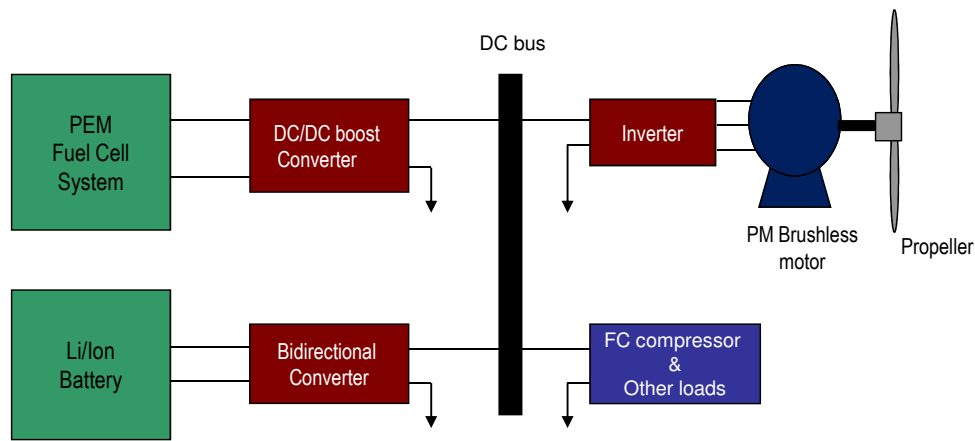


Figure 6.1: *Regulated hybrid power system*

system, the battery power usage is lower than the battery used in unregulated architecture. Therefore, the size and the weight of the battery used in the regulated power management architecture are lower than the unregulated hybrid system battery. Figure (6.1) shows the schematic diagram of the regulated hybrid power architecture.

The propulsion system power demand is varied with the UAV speed in the different flying modes such as the take-off, the climb, the cruising, the endurance and the landing as described in chapter (4). The DC bus current which is illustrated in figure (6.2), shows the load current variation at DC bus during the mission. The power management algorithm is developed based on the three power stages called, Start-up state, Battery charging state and High power state to react these load current variations. The flow chart of the power management algorithm is shown in figure (6.3).

6.2.1 Start-up State

The fuel cell system requires extra time for the air blower to reach appropriate airflow rate and needs self-heating process to generate the electricity. Therefore, the Start-up state is introduced to accelerate the fuel cell initial reaction by starting the fuel cell system balance of plant before connects the load current to the fuel cell system. Initially, the controller measures the battery terminal voltage and assures the battery has enough power to power the fuel cell system BOP. If the battery terminal voltage is less than cut-off voltage 10V, an external power supply is necessary to start the PEM fuel cell system balance of plant (BOP). After 120 seconds, the propulsion motor is started and increases the throttle until the fuel cell system power output reaches to the fuel cell rated level (14V @ 7.2A). At this stage, the BDC controller reduces the high voltage

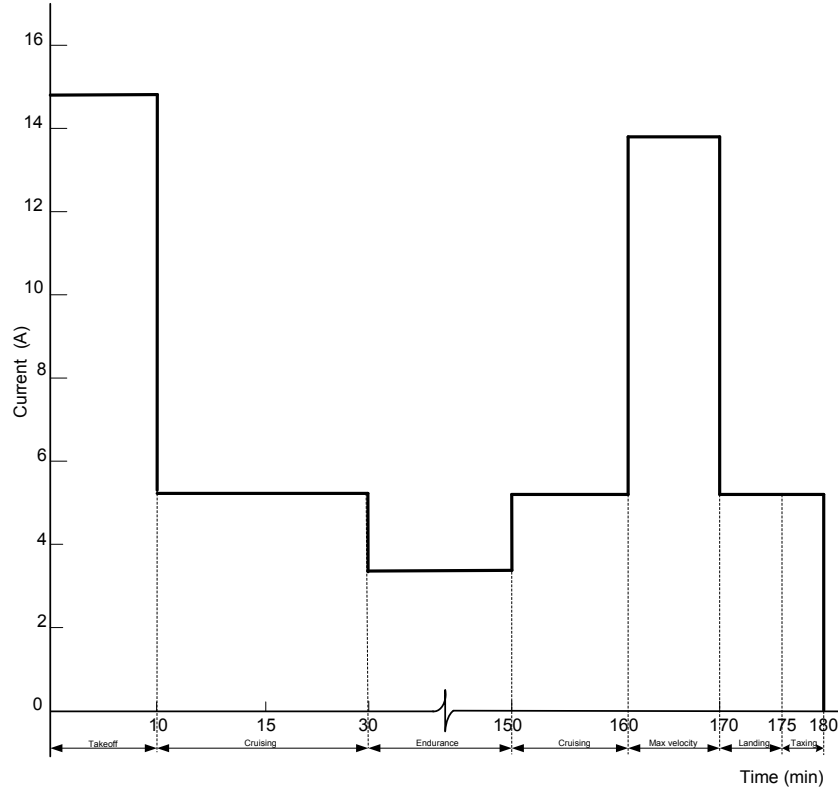


Figure 6.2: DC bus current variations during the mission

(HV) side voltage to activate the UDC operation. Figure (6.4) shows the power flow diagram during the Start-up state.

6.2.2 Charging State

The Charging state can be activated at two stages where, before the aircraft take-off and while the aircraft is operating at the endurance mode. After the start up process, if the battery SoC is not sufficient to take-off which is the battery terminal voltage is $V_b \leq 12V$, the battery charging state is activated. At this stage the fuel cell system is operated at the rated power and the BDC is switched into the buck mode. During the battery Charging state, the fuel cell system supplies the power to the propulsion system, fuel cell system BOP and to the other electrical devices until the battery terminal voltage reaches $V_b = 12V$. Figure (6.5) shows the power flow direction during the battery Charging state.

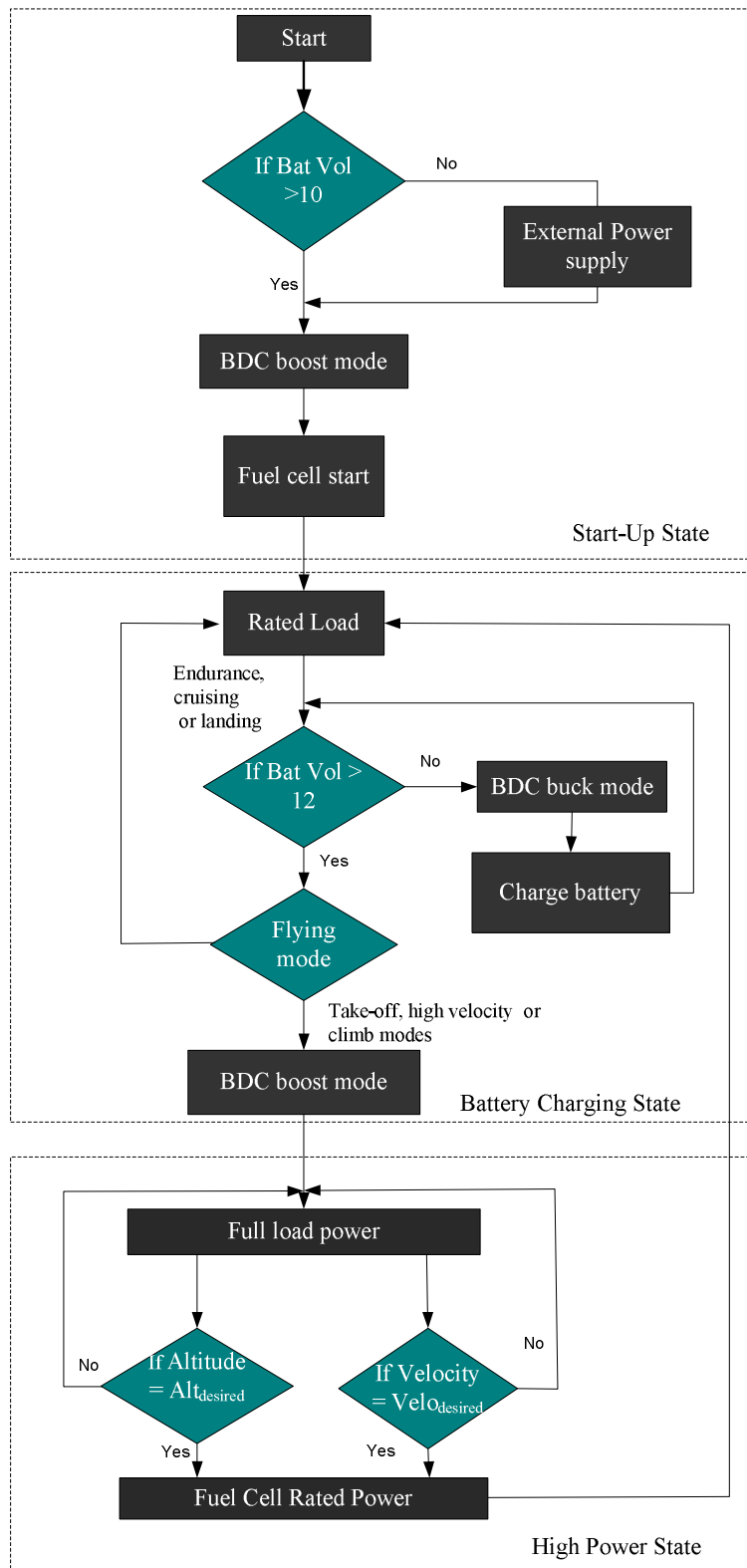


Figure 6.3: Power management system decision flow chart

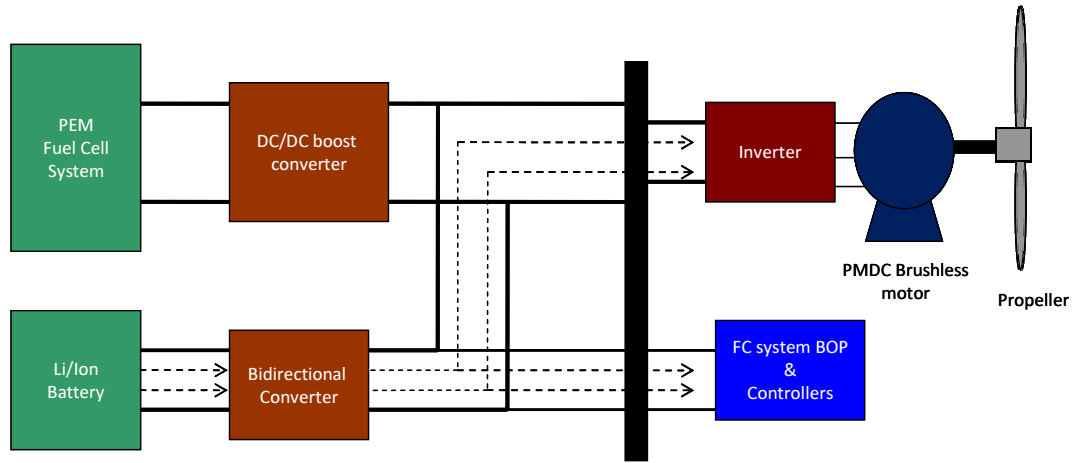


Figure 6.4: Power flow during the Start-up state

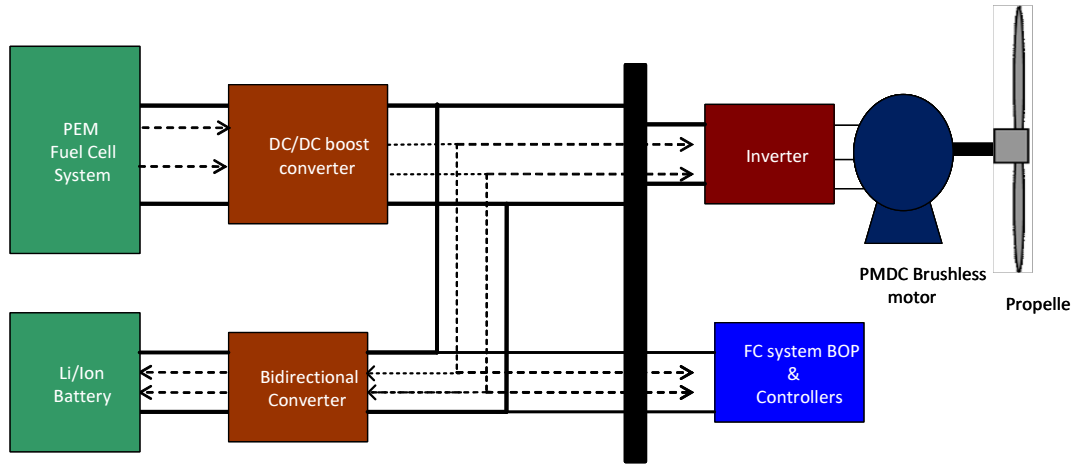


Figure 6.5: Power flow during the Charging state

The battery Charging state is again activated during the aircraft endurance mode. The battery charging time is depended on the remaining battery charge. However, the proposed Li-Ion battery should charge at least 3 hours to reach from cut-off voltage to the fully charge voltage.

6.2.3 High Power State

The BDC is switched into the boost mode when the battery is charged up to $V_b = 12V$. Then the load power can be is increased up to the maximum velocity or the climb power. During the high power state, the flight controller should check whether the

aircraft is achieved its desired altitude or velocity and before switches back into the cruising power. When the propulsion system is operated in the initial climb mode after the take-off, the power management system decisions are remained with the high power state until the UAV reaches to desired altitude. In addition to the take-off and the climb powers, when the aircraft flies at higher velocity which demands the DC bus current greater than $5.3A$, the power management system operates in the high power state. The power flow diagram of the high power state is shown in figure (6.6).

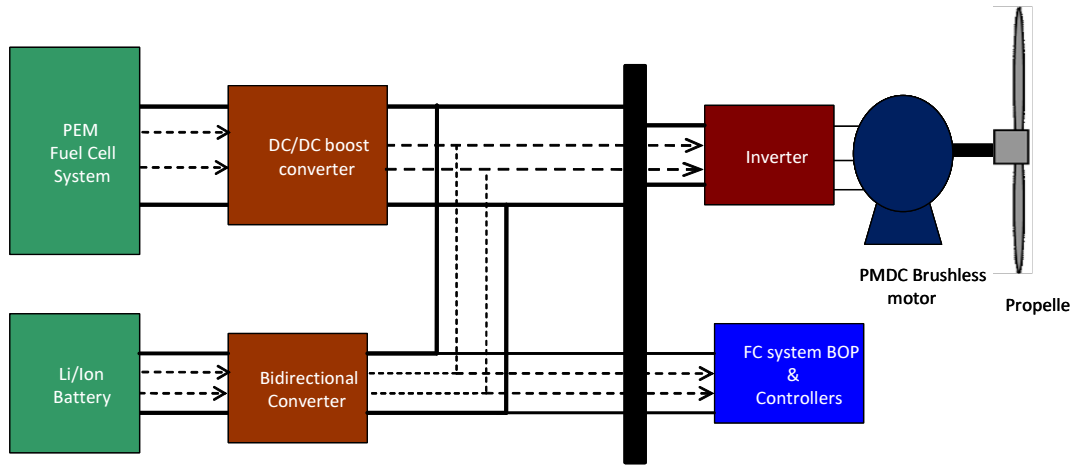


Figure 6.6: Power flow during the high power mode

The power management algorithm illustrated in (6.3) shows that the power management decisions are based on the feedback received from the battery voltage and the load current. The voltage and the current boundary conditions for the each power source are determined based on the battery and the fuel cell system power capacities. The power management system decides the operating modes for the UDC and the BDC by considering both the feedback signals and power capacities. For the Start-up mode, the cruising mode and the endurance mode, the propulsion system power can be increased up to the $125W$ DC bus power. If the FC-UAV flies at higher velocity or higher climb rate that need more power than $125W$, the operating state is switched to the high power state. The boundary conditions defined for the DC bus current at different flying modes are shown in figure (6.7).

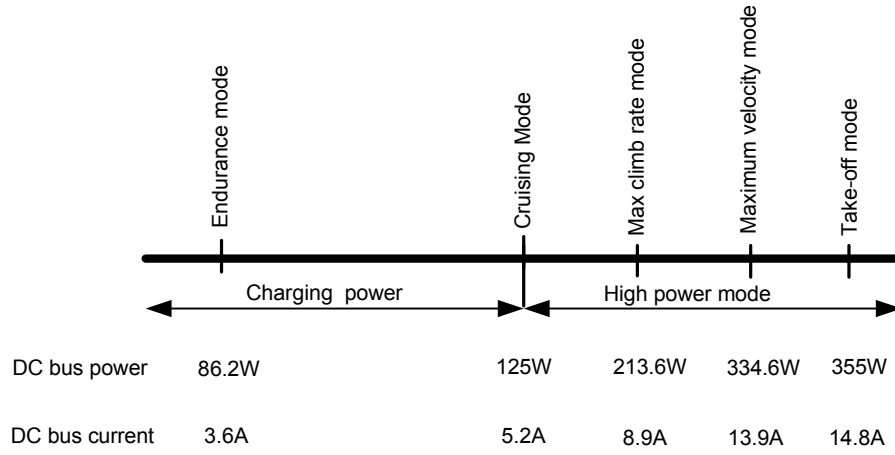


Figure 6.7: Boundary conditions for the operating modes

Figure (6.7) shows that after the DC bus current exceeds 5.3A at 24V dc bus voltage, the operating power state is changed to the high power state. At initial stage, if the battery charge is not sufficient for the take-off, the power management system changes the operating state to the Charging state. When the aircraft is takeoff or trying to achieve its desired altitude in the climb mode or the desired velocity in the level flight operation, the power management system activates the high power state. If the aircraft is flying at endurance mode where the DC bus current is lower than 5.3A, the power management system operating power state is switched back to the Charging state.

6.3 Fuel Cell Power Conditioning Unit

The PEM fuel cell system rated power is considered as the most efficient and stable operating point during the hybrid propulsion. Table (5.7) shows that the 100W Horizon fuel cell system rated voltage and current are 14V and 7.2A respectively. The 100W PEM fuel cell system has wide voltage output range varied from 13V to 23V. The PEM fuel cell system has designed to deliver high current with low operational voltage. However, the fuel cell system voltage can not fluctuate with the current similar to the battery due to the delay in the chemical reactions. Therefore, the fuel cell system's power conditioning unit is developed with the unidirectional power converter,

the voltage mode and the current mode controllers.

The electric propulsion system which described in chapter (5) is operated at 24V nominal voltage. In order to coincide the fuel cell system voltage with the DC bus, the PEM fuel cell system voltage at rated power is stepped-up from 14V to 24V. The non-isolated unidirectional converter is used as the power conditioning unit to step-up the fuel cell voltage to the DC bus voltage. The voltage control loop and the current control loop are introduced to control the UDC. The UDC can be operated in a constant voltage control mode or in a constant current limit control mode depending on the power management system requirement. During the charging power state, the UDC maintains the constant voltage output at 24V. The UDC current limit mode is activated during the high power state to share the load current with the battery. Throughout the high power state, the UDC current controller maintains constant current and allows the voltage output to vary with the BDC output.

6.3.1 Unidirectional Converter Voltage and Current Limits

The UDC maximum input power from the fuel cell system is 140W. The UDC high voltage (HV) side is constant at 24V during the constant voltage control mode. The UDC efficiency is considered 0.88 at the rated power. The UDC maximum HV side current at charging power mode is shown in (6.1).

$$I_{UDC(HV)}^{max} = \frac{P_{fc} \times \eta_{UDC}}{V_{DC_{bus}}} \quad (6.1)$$

$$I_{UDC(HV)}^{max} = \frac{140W \times 0.88}{24V} \quad (6.2)$$

$$I_{UDC(HV)}^{max} = 5.2A \quad (6.3)$$

During the UDC current control mode, the UDC HV side current is constant at 5.2A and in the voltage control mode, the HV side voltage is fixed to 24V.

6.4 BDC Voltage and Current

The BDC can operate as a buck converter during the Charging state and switches into a boost converter when the Start-up or the high power states are activated. The BDC is controlled in the voltage control and current control mode as necessary. The constant voltage at the boost mode of the BDC is defined as V_{BDC}^{HV} and the constant voltage output at the buck mode is V_{BDC}^{LV} . The limiting current of the BDC buck and boost modes are $I_{BDC_{HV}}^{max}$ and $I_{BDC_{LV}}^{max}$. When the BDC is in the buck mode, the battery is charged by the current control mode. From the battery specifications, the charging current is $85mA$ and the charging voltage should above $13.0V$. Therefore, $I_{BDC_{LV}} = 85mA$ and the $V_{BDC}^{LV} = 13.0$. During the BDC boost mode, the $V_{BDC}^{HV} = V_{DC_{bus}}$. When $V_{BDC}^{HV} > V_{DC_{bus}}$, the fuel cell system current is zero due to the higher feedback voltage in the UDC. Therefore, the BDC HV side voltage is maintained at higher than the DC bus voltage during the Start-up period and later reduces to the lower value than the DC bus voltage. The V_{BDC}^{HV} is ranged from $16V$ to $30V$.

6.5 Operation Principle

The hybrid power system load sharing sequences at the Start-up state described in the flow chart (6.3) and graphically represented in figure (6.8). In order to respond the DC bus current, the UDC and the BDC current control and the voltage control modes are switched between each other. When the propulsion system is started, only the battery provides the propulsion power. From time $[0 \rightarrow t_2]$, the motor controller gradually increases the load up to the rated level. At this stage, the UDC current is remained in zero and the BDC current is increased. At t_1 , the $V_{BDC}^{HV} = V_{DC_{bus}}$. The Start-up process is last long until t_2 where, the BDC current starts to decrease to $0A$ while the UDC current is increased. After t_2 , the UDC is operated in the constant voltage mode where $V_{UDC}^{HV} = V_{DC_{bus}}$. If the battery voltage is less than $10V$ at zero I_{BDC} , the power management system starts to charge the battery until $V_{bat} = 12V$. During the t_3 to t_4 , the high power mode is activated for the aircraft take-off and the initial climb. At this stage, the UDC operates in the current control mode and maintains the constant $I_{UDC} = 5.2A$. During the t_3 to t_4 , the BDC operates in the boost mode and the voltage controller

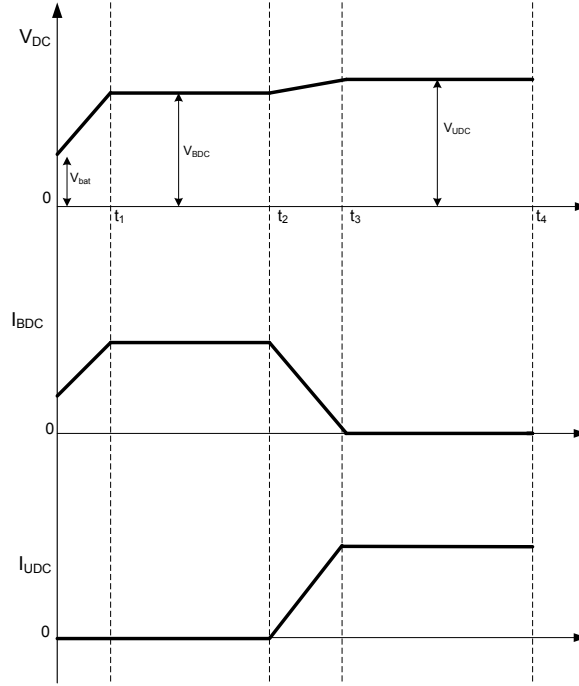


Figure 6.8: DC bus current distribution during the Start-up process

brings the $V_{DC_{bus}} = V_{BDC}^{HV}$. After the t_4 , the propulsion system operates in the cruising mode and the endurance mode and hence power management system switches into the charging power state. At this power stage, the UDC operates in the voltage control mode and the BDC charges battery at the constant buck voltage $V_{BDC}^{LV} = 13.0$.

When the aircraft operates in the high velocity which demands the DC bus current greater than $5.3A$, the BDC is switched back to the boost mode. At this period, the UDC is in the current control mode and the BDC is operated in the voltage control mode.

6.5.1 Voltage Mode Controller

A typical switching power converter consists of an analog control scheme with error amplifiers and gain controllers. The scaled voltage output is compared with the referenced value and the amplified error is applied to a compensator. In the variable frequency converters, the compensator gain is determined by considering the stabil-

ity of the power converter. In the digitally controlled power converter, the feedback process which has error signals, compensator and PWM signal generation is entirely managed by the micro-controllers. Author selected the digital control technique for the power converters due to the simplicity of the design and constant operation frequency. If the digital control power converter switching frequency is a constant value the stability analysis is not necessarily for designing process. Therefore, the author selected the constant converter switching frequency at 20kHz. The sensor signal of the converter high voltage side is converted in to a digital value by using the A/D module of the microcontroller. Then, the referenced value which is 24V for voltage control mode is compared with the actual value and the error value is generated. The microcontroller program consists of these error generating sequences and then this voltage error is converted into a PR value to decide the duty ratio of the PWM signal. Author will describe the related derivation for PR value in chapter (8). By changing the PR value of the PWM module, the duty ratio of the PWM signal can be changed. The increased or decreased of the duty ratio depend on the error. The micro-control architecture generates the required PWM signal to regulate the power converter output.

The voltage mode control scheme is designed to maintain a constant voltage at desired level depending on the load power requirement. Figure (6.9) shows the schematic diagram of the voltage mode controller. The resistive voltage divider is used to get the actual voltage feedback from the UDC HV side. k is a voltage reducer designed to match the controller input voltage requirement. The voltage error V_e between the actual voltage V_a and the reference voltage V_{ref} is fed in to the PWM generator. Based on the voltage error, the duty ratio (D) of the PWM signal is varied. The microcontroller based pulse width modulation is developed for this hybrid application and more detailed description about the embedded control is described in chapter (8).

6.5.2 Current Mode Controller

The current mode controller is used in the high power state in order to maintain required current level in the power sources. The current controller senses the converter actual current and compares with the referenced current value defined for the particular flying mode. The currents required for the take-off, the climb and the high velocity

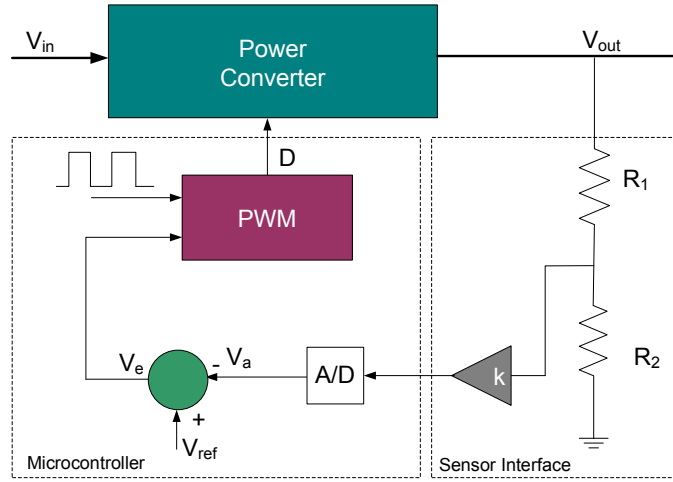


Figure 6.9: *Voltage mode controller*

which defined in the figure (6.7) are used as the referenced values. The current compensator reduces the error between the actual current and the referenced value. Figure (6.10) shows the schematic diagram of the current mode controller. The DC bus current sensor (H) senses the load current and the controller generates the required duty ratio for the converter.

Table (6.1) shows the control modes of the UDC and the BDC at the high power and the charging power states.

Table 6.1: *Operating modes of the power converters*

Power Converter	$0 < I_{dc} \leq 5.3$	$5.3 < I_{dc}$
UDC	Voltage Mode	Current Mode
BDC	Current Mode	Voltage Mode

6.6 Simulation

The Power Management System which described in section (6.2) is developed in Matlab Simulink environment and the hybrid system power architecture is modeled in the Sim-

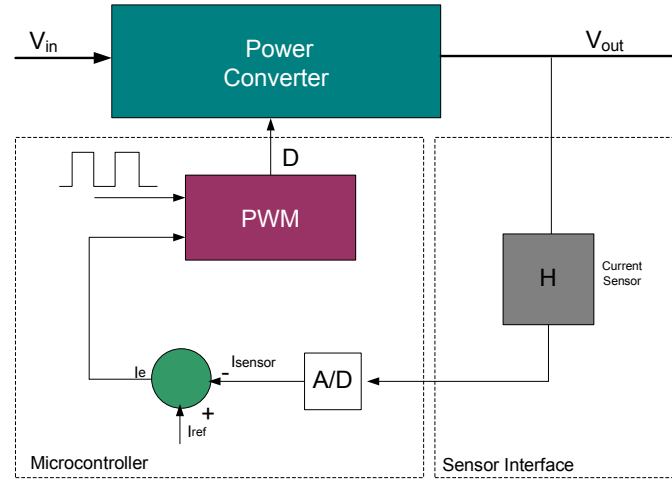


Figure 6.10: *Current Mode controller*

power System toolbox as the implementation framework. For the power management simulation, a finite state machine is modelled to run the power management decisions. The Start-up state, the charging power state and the high power state are represented as the event driven states. The switching sequences described in the power management algorithm are implemented through transition actions. In the Simpower system simulation, the PEM fuel cell and the Li-Ion battery power system are modelled with a unidirectional power converter and a bidirectional power converter. A permanent magnet brushless motor with a three phase inverter is used as the propulsion load. The control sequences generated by the finite state machine are used to control the Simpower System simulation model.

6.6.1 Finite State Machine Simulation

The finite state machine is developed to simulate the power management decisions taken for the Start-up state, the Charging state and the High power state. The power switching stages between the battery and the fuel cell system are implemented as the state transition sequences. The first state machine is developed for the Start-up process and the initial charging. The High power state and the Charging power state transitions are implemented using second state machine. The developing stages of the state machines for the each power mode are described in the following sections.

6.6.2 Start-up State Transitions

The fuel cell system Start-up process is a slow process caused by the delays in the fuel cell reactions and the stack heating. Therefore, the battery is used to supply the initial power to the propulsion system and to the fuel cell system BOP. After powering the BOP, the fuel cell system start up time is given as 30 seconds by the fuel cell manufacturer [69]. However, for the safety of operation and to give more time space for the controllers, the total Start-up time for the hybrid system is considered 100 seconds including the time taken by the propulsion system to reach the rated power. As illustrated in the figure (6.8), from time 0 to t_1 , the BDC HV side voltage (V_{BDC}) is increased up to the rated DC bus voltage. The constant power mode is maintained between t_1 to t_2 period. The fuel cell system BOP Start-up process is completed at time t_2 . Then, the fuel cell system is started to generate the electricity and the UDC is gradually boosted voltage output during the t_2 to t_3 period. The battery charging process is started at t_3 and last long until the battery voltage reaches to 12V. The battery charging time is depended on the state of charge of the battery and can be taken up to several hours. For the simulation purposes, the charging time is limited to t_4 and the high power mode is activated after t_4 .

Figure (6.11) shows the Matlab simulation model developed for the hybrid system Start-up process. During the Start-up process, the initial power source selecting sequence is implemented by using the multi-port switch which selects the battery or the external power supply to power the load. Depending on the battery terminal voltage, the multi-port switch changes the active power source. The finite state machine activates *PWM2* which is the BDC HV side PWM signal to boost the battery voltage. After time t_2 , the *PWM2* signal duty ratio is gradually reduced to zero and *PWM3* signal is activated to boost the UDC voltage. The figure (6.8) illustrates that the UDC current is increased to the rated power level at the end of time t_3 . From t_3 to t_4 , the DC bus voltage is controlled at V_{UDC} level. Figures (6.12) and (6.13) show the state machine and the Simulink model developed for the Start-up process.

In the Start-up state machine, the BDC ON and OFF states are triggered by the *SWITCH* signal which is generated by the multi port switch based on the power sources availability. However, for the simulation process, the initial battery voltage is maintained

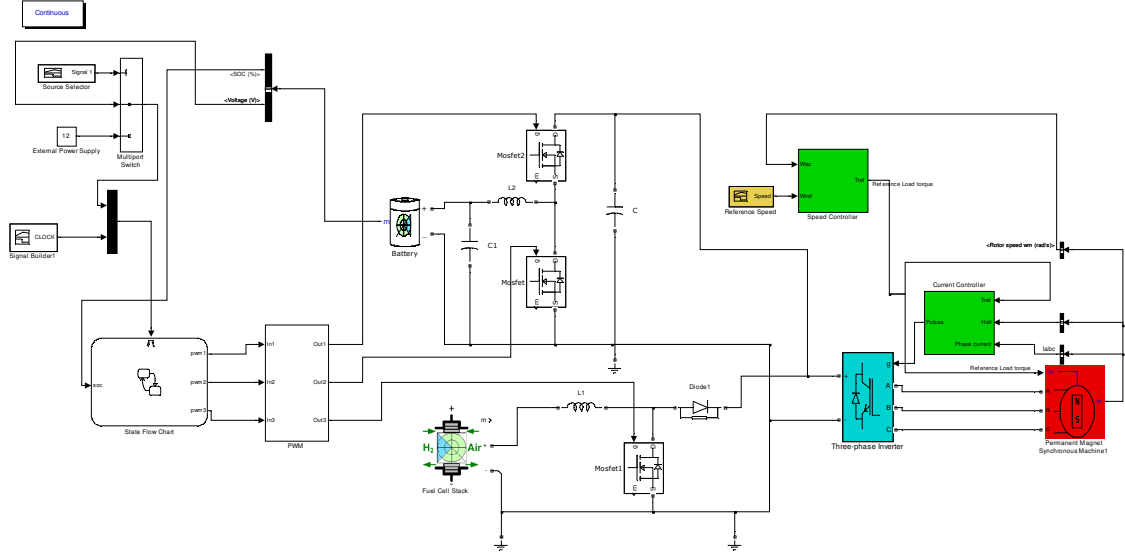


Figure 6.11: Circuit diagram of the Start-up state

at the 12.2V to use as the Start-up power source instead of the external power supply. The Start-up state machine is consisted with six states, *power-on*, *power-off*, *boost-on*, *boost-off*, *buck-on* and *buck-off* states. The state machine default states are the *power-off*, *boost-off* and the *buck-off*. When the battery SoC is greater than 12V, the BDC *power-off* state is changed to the *power-on* state by the *SWITCH* state action. In side the *poweron* state, there are two parallel states called *Start-up* and *charging*. The first state sequence is *startup* and the second is the *charging*. The BDC starts with *boost-off* state and if the BDC LV side terminal voltage is grater than 12V which is $V_{ol} \geq 12$ condition is satisfied, the active state moves to the *boost-on* state. When the BDC LV is lower than 12V, the BDC moves into the *Charging* state and transits from the *buck-off* to *buck-on* action. In side the *power – on* state machine, the *boost-on* and the *buck-on* states are not taken place at the same time. During the *boost-on* and the *buck-on* states, the relevant PWM switches are moved to logic 1 state to activate power converter operating mode.

6.6.3 High Power State Transitions

During the high power state, the UDC is operated in the current controlled mode and the BDC regulates the DC bus voltage. After the Start-up state, the load current is

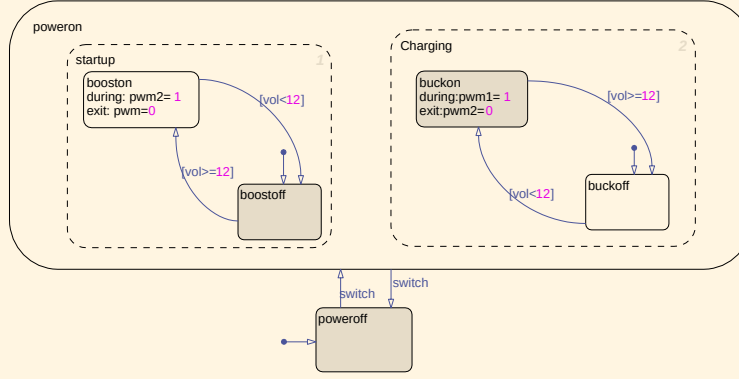


Figure 6.12: State machine developed for Start-up event

increased for the aircraft takeoff. Figure (6.14) shows the current distribution between the UDC and the BDC during the high power state.

After the Start-up state is ended at t_4 , the aircraft take-off power is applied and last long until t_6 . The UDC and the BDC are operated in the boost mode to supply the peak power. During the take-off mode, the DC bus voltage is dropped down to the BDC HV output and the UDC is operated in the current controlled mode. The UDC HV side voltage output is less than the DC bus voltage. After time t_6 , the cruising and endurance modes are activated until time t_8 . The battery charging process is started from t_6 and ends at t_8 . The UDC boosts the DC bus voltage up to the V_{UDC} . During the maximum velocity mode which starts from t_8 , the load current is increased higher than the rated value. Hence, both the fuel cell system and the battery start to supply the load demand. While the UDC is operating at the current control mode, the BDC regulates the DC bus voltage at V_{BDC} .

The second steady-state machine developed for the high power state and the level flight operation which has similar characteristics to the Start-up state machine. However, the state transitions are occurred based on the load current signal. When the load current is exceeded the rated current level, the UDC and the BDC are switched to the boost mode simultaneously. When the aircraft is operating at level flight operation such as

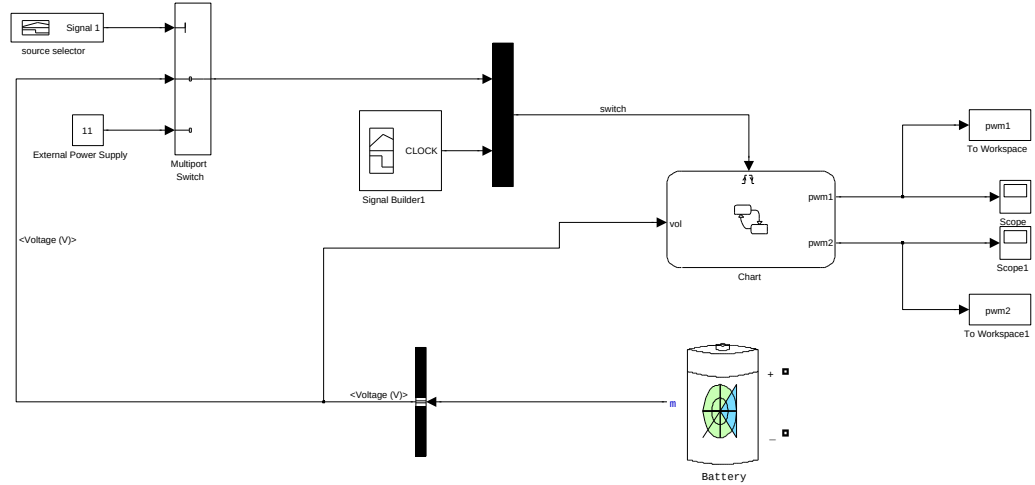


Figure 6.13: Simulink model for the Start-up state

the cruising and the endurance, the BDC switches back to the buck mode to charge the battery. Figure (6.15) shows the developed second state machine for high power state.

6.7 Simulation Results

The hybrid system developed in the Simpower system toolbox is simulated with the finite states machines developed for the Start-up state and the high power state. These state flow machines are operated as the implementation protocol for the power management decisions. In the State-flow simulation, synchronization of the states machines control parameters which are the battery terminal voltage and the DC bus current into one states machine was challengeable and ended up with simulation error caused by the delay in Simpower system output signals. Due to these simulation difficulties, the power management algorithm is simulated in two stages, consequently the startup state with the initial charging and the high power state with level flight operation. The first state machine which includes the Start-up switching sequences is controlled by the battery terminal voltage. The second state machine which consists of the high power state and the level flight operations sequences is controlled by the load current. How-

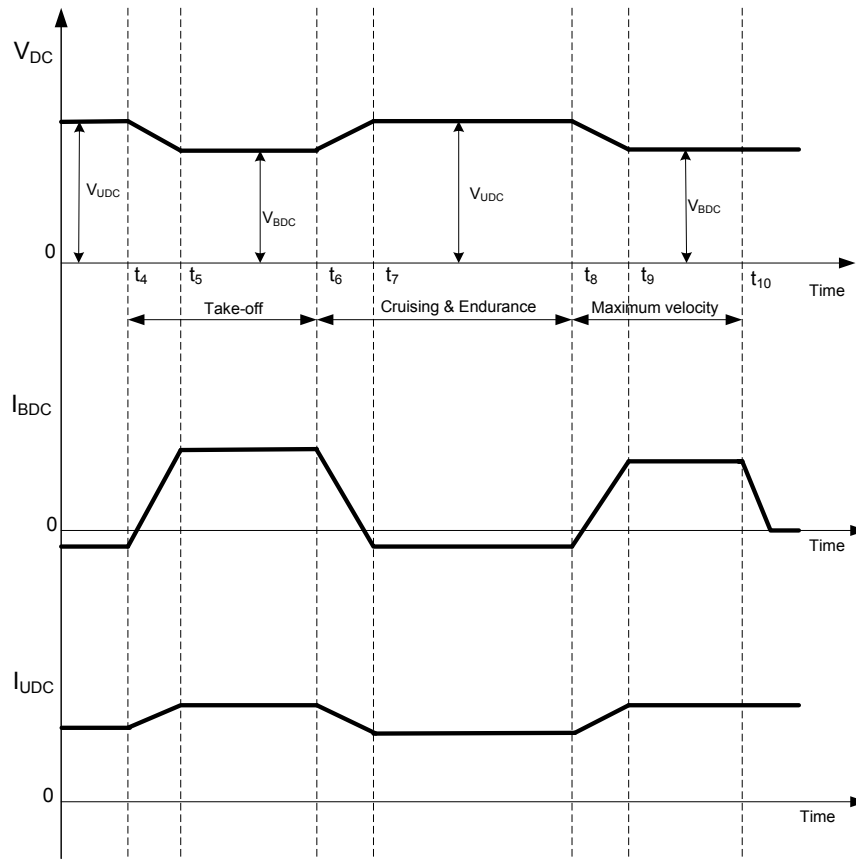


Figure 6.14: DC bus voltage and power converters HV side current variations during the high power state

ever, simulation results are represented without discontinuing throughout the mission.

The characteristics of the modelled hybrid system and the power management architecture are verified by simulating the two mission profiles which have different power requirements. In case study (i), the simulation time is reduced to 10 minutes rather than actual 1 hour mission due to the slowness of the simulation. For case study (ii), the aircraft speeds are changed and hence the propulsion power values are varied from the case study (i).

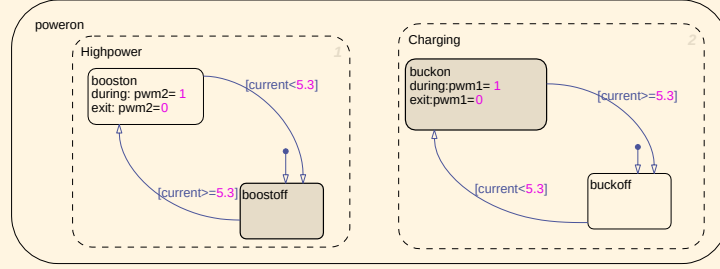


Figure 6.15: State machine for the high power state and the level flight operation

6.7.1 Case Study (I)

In the first case study, an ISR mission is introduced with all the possible flying modes of the UAV. Figure(6.16) shows the DC bus current variations during the mission. This mission includes the Start-up state and the take-off mode with the initial climb. Then, the UAV is flown at the cruising mode until t_4 and changes to the endurance mode. After t_5 , the UAV is flown back to the launching site with the maximum velocity mode. Figure (6.17) shows the expected currents distributions of the BDC and the UDC.

Figure (6.18) shows the DC bus current demanded by the propulsion system during the mission. Initially, the motor current was gradually increased up to 3A. After the 100 seconds, the take-off power was applied and the DC bus current was roused to 14.8A. The take-off duration was limited to 60 seconds. After 160 seconds, the propulsion system changed to the cruising mode and the DC bus current was reduced to 5.2A for a 2 minutes period. Then the endurance flying mode was applied and the DC bus

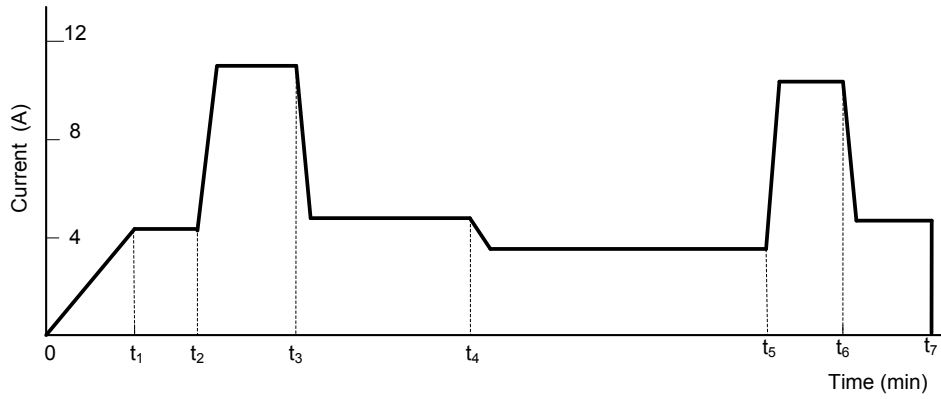


Figure 6.16: DC bus current variations during the mission (I)

current was minimized to 3.6A. The endurance mode was remained for 200 seconds time period. The maximum velocity power mode was applied after 8 minutes and remained in 60 seconds period. At the last part of the simulation, the propulsion system current was reduced 5.2A for the loitering and landing purposes.

The load power distribution between the UDC and the BDC are shown in figures (6.19) and (6.20). During the Start-up state, the UDC current was gradually increased after 40 seconds. After the 40 seconds, the BDC current flow was gradually declined. At 100 seconds, the UDC current was 2A and the BDC current was 1A. Then, the power management system activated the high power state and at the same time, the power electronic interface changed the UDC operating mode into the current control mode. The UDC current was regulated to the maximum 5.2A and at this stage the fuel cell system was operated at the maximum current 10.8A. During the high power state, the BDC was operated in the voltage control mode and supplied 9.6A current. When the Charging state activated, the UDC was switched into the voltage control mode and the BDC was in the buck mode and regulated the current for the battery charging.

Figures (6.21) and (6.22) show the fuel cell system voltage and the current variations during the mission. The fuel cell system current was maximized during the high power state and reduced during the charging power state. The battery SoC variation during the mission is shown in figure (6.23). The battery SoC was reduced during the high power state and the charge level was gradually increased at the charging power state. The simulation results obtained from the case study (I) show the successful implementation of the proposed power management system. The DC bus current is distributed

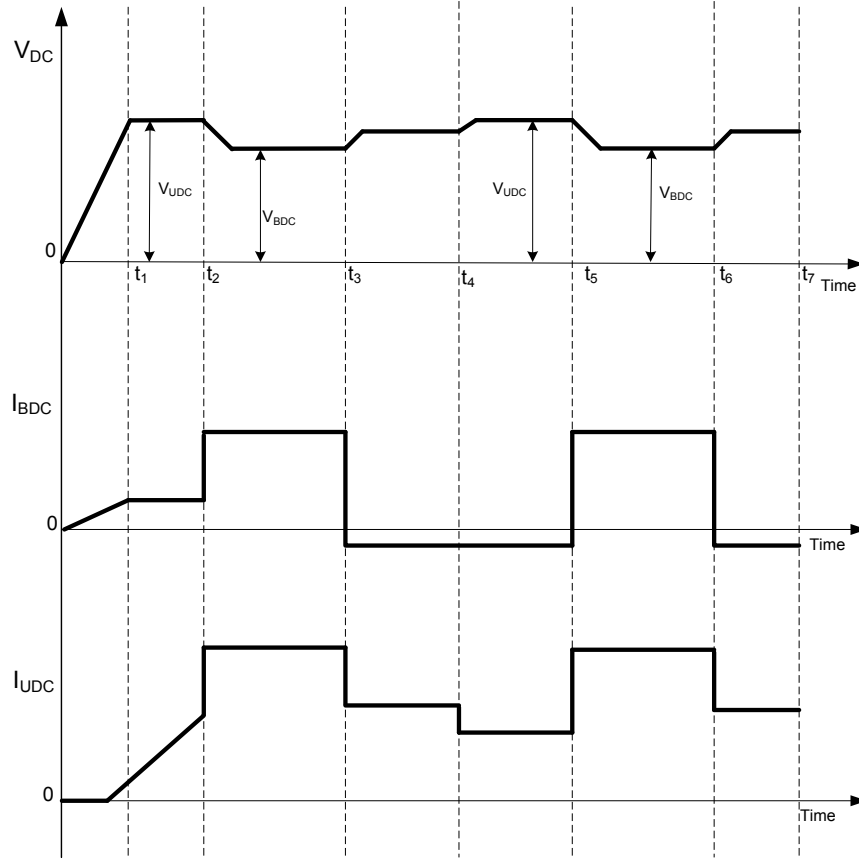


Figure 6.17: Current distribution between the UDC and the BDC

according to the power states such as the Start-up, the charging and the high power mode. The voltage control mode and the current control mode are switched at the appropriate stages and obtained the fuel cell current profile for the fuel cell performance optimizations.

6.7.2 Case Study (II)

Case study (II) is introduced to verify the proposed power management system performances in a different power profile. A new mission profile is simulated in the same hybrid configuration and the results are illustrated to identify the performances similarities in the power management system. Figure (6.24) shows the DC bus current profile. The Start-up, the take-off and the initial climb were remained as the mission (I). After the initial climb, the aircraft was started to fly in the maximum velocity mode.

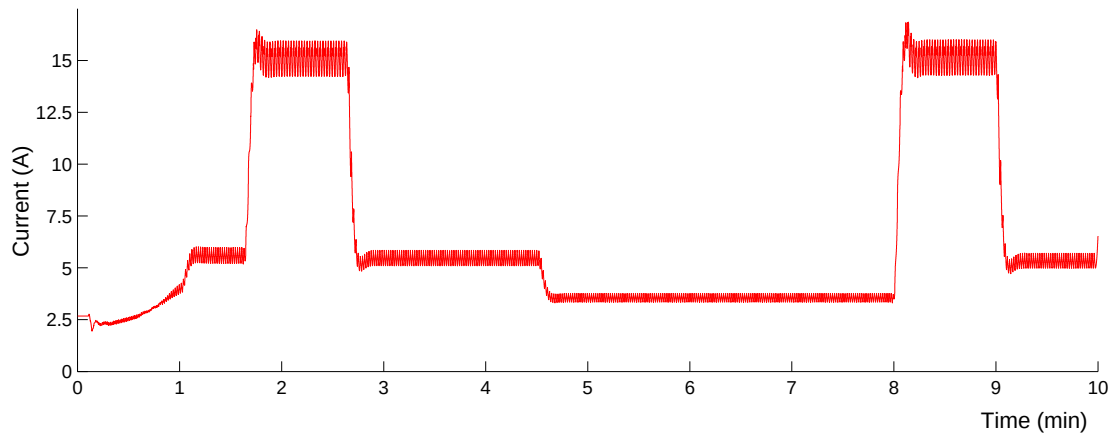


Figure 6.18: *DC bus current variations during the simulation*

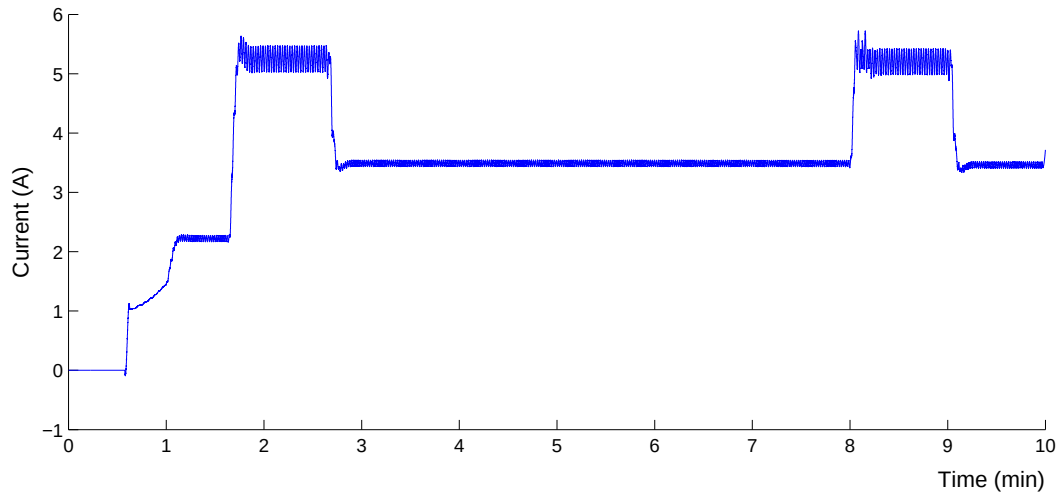


Figure 6.19: *UDC HV side current variations.*

After 4 minutes and 30 seconds, the UAV endurance flying mode was activated. After 8 minutes, the aircraft started the maximum velocity mode again during the return path. The loitering and landing currents were considered as same as the mission(I).

The DC bus current was distributed between the fuel cell and the battery according to the power management system state changes. Figure (6.25) and (6.26) show the current distribution between the UDC and the BDC. The current distribution during the Start-up state, the take-off and initial climb were similar to the mission (I). After 160 seconds, the propulsion system demanded 4A current from the UDC and the BDC supplied the 6A current at the maximum velocity power state.

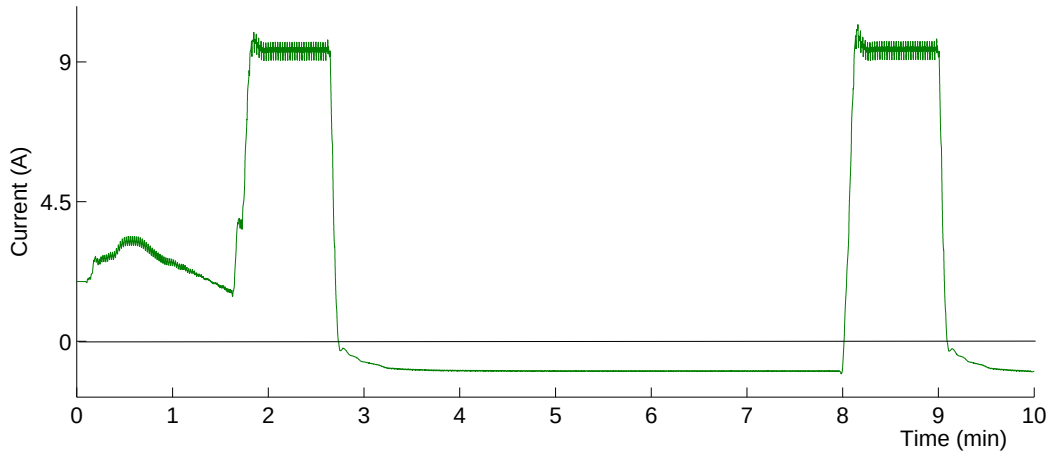


Figure 6.20: *BDC HV side current variations.*

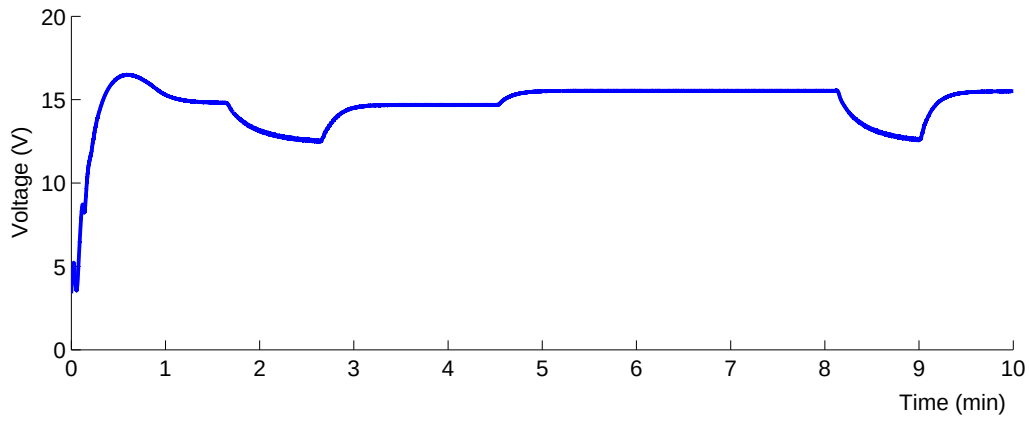


Figure 6.21: *Fuel cell voltage variations*

Figure (6.27) and (6.28) show the fuel cell current and the voltage variation during the mission (II). During the high power state, the fuel cell current was maximized to 9.8A. At the low power demand stages the fuel cell operational power was reduced to and hence the cell voltage was increased.

Figure (6.29) shows the battery SoC variation during the mission. The battery SoC was increased during the endurance mode and reduced during the high power states such as the take-off, the initial climb and the maximum velocity.

During the mission (I) and the mission (II), the power management system shows the similar performance characteristics in terms of the hybrid system power sharing. There-

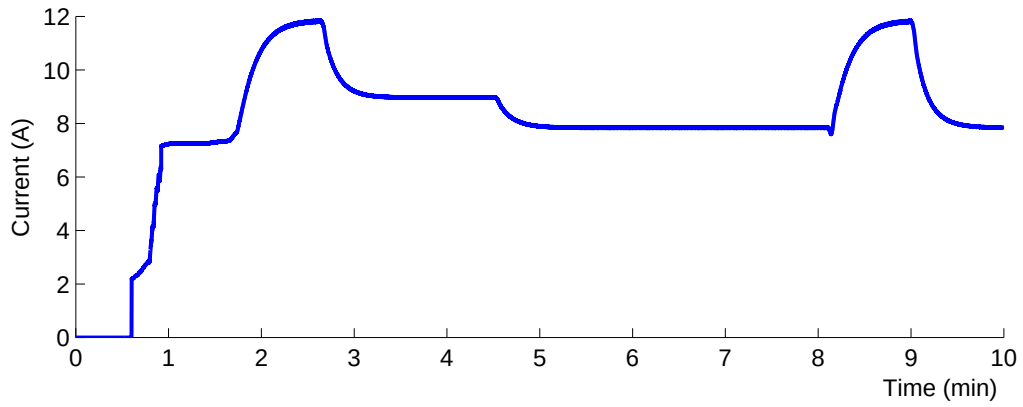


Figure 6.22: *Fuel cell current variations*

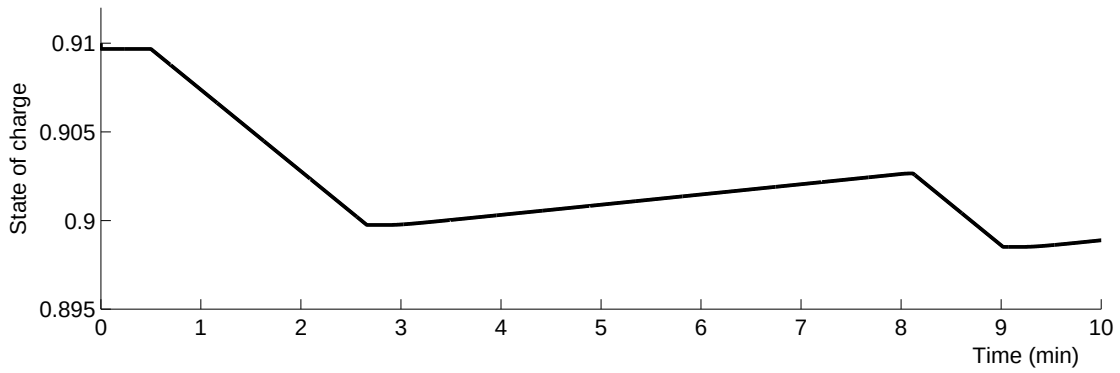


Figure 6.23: *Battery SoC variations*

fore, the proposed power management algorithm can be validated to use in the hybrid system power architecture. The main objective of the power management system was to obtain the controlled fuel cell current for the fuel cell optimization process. Chapter (7) will discuss the fuel cell performance optimization based on the fuel cell current obtained in the power management system.

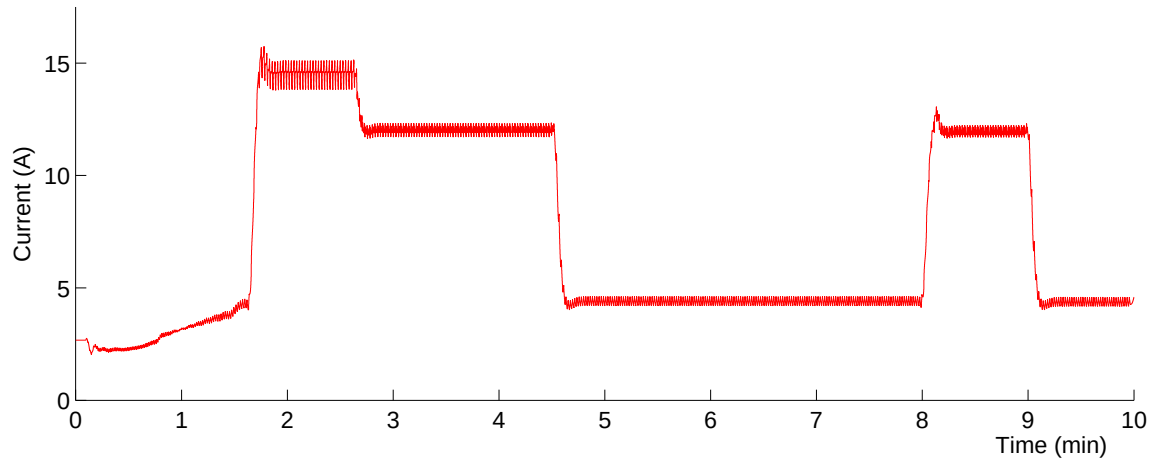


Figure 6.24: *DC bus current variations in mission (II).*

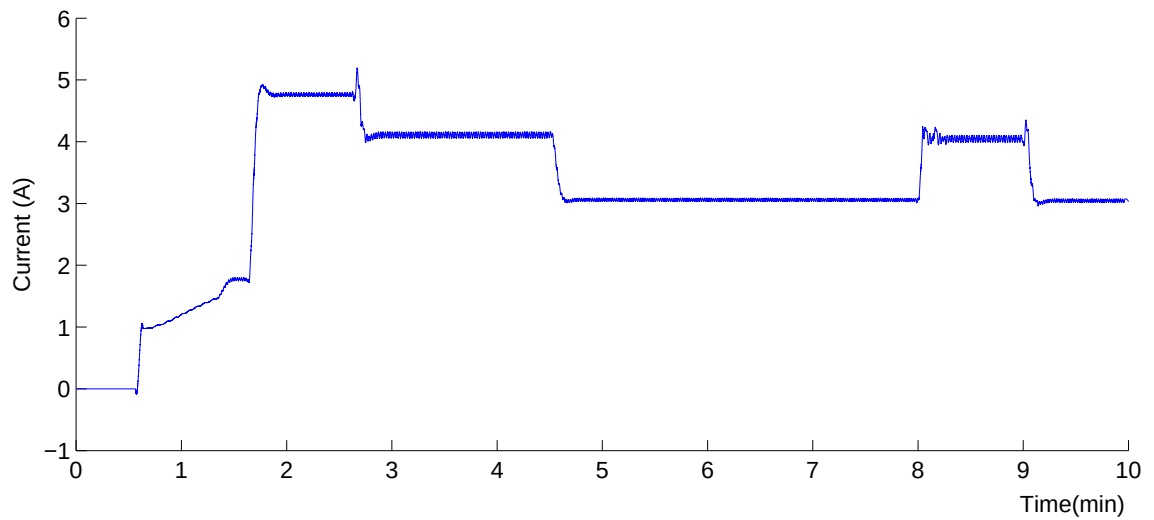


Figure 6.25: *UDC current variations in mission (II).*

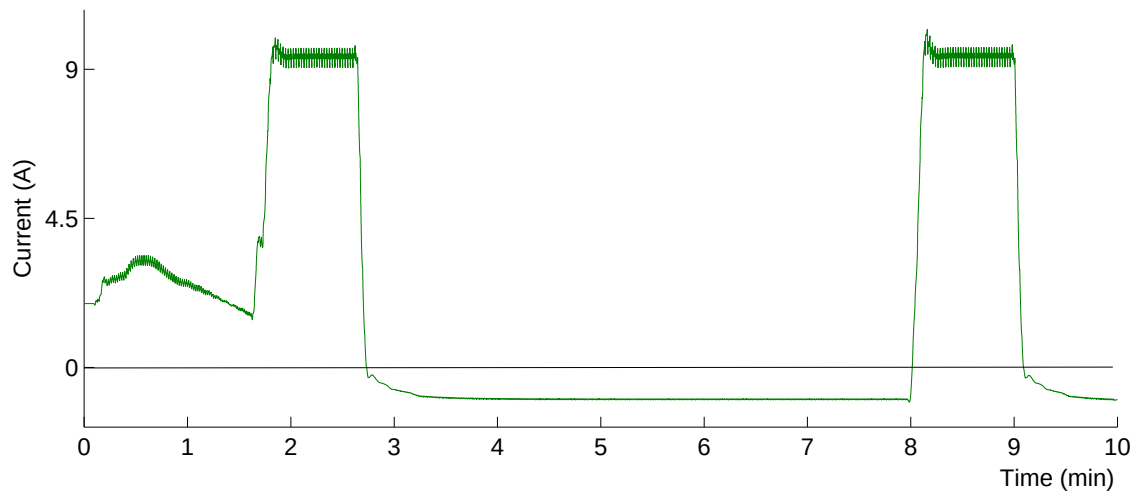


Figure 6.26: *BDC current variations in the mission (II).*

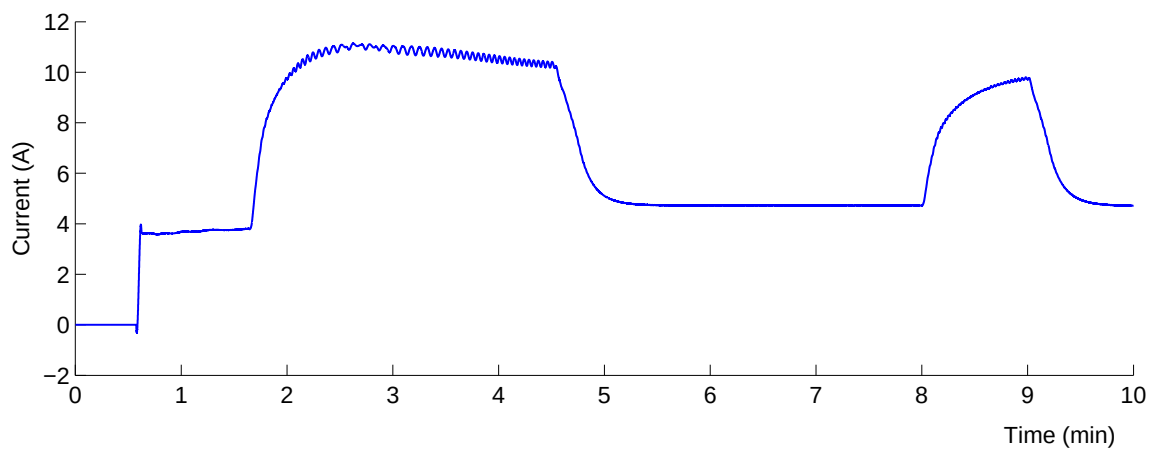


Figure 6.27: *Fuel cell current variations in the mission (II).*

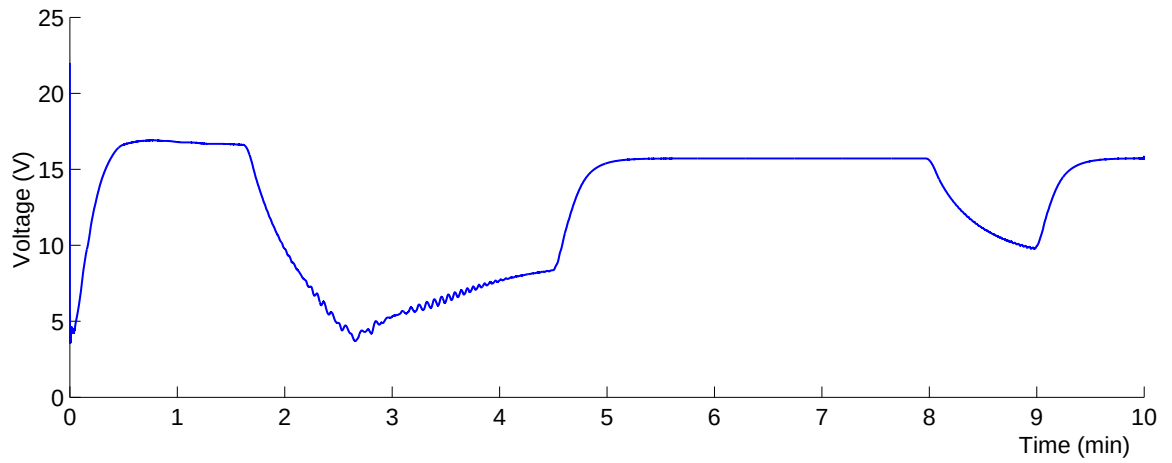


Figure 6.28: Fuel cell voltage variations in the mission (II).

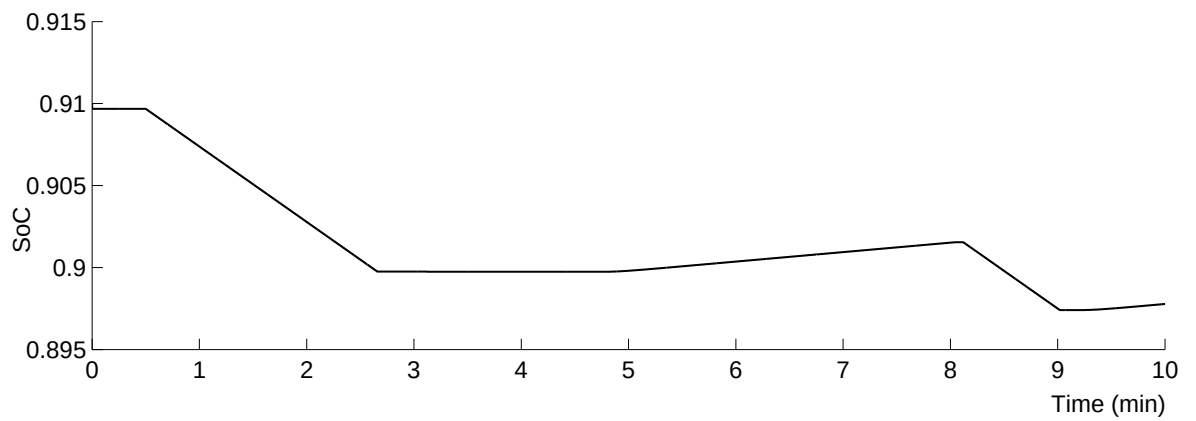


Figure 6.29: Battery SoC variations during the mission (II).

Fuel Cell Control and Power Management

Extending the benefits of the regulated hybrid power system, an adaptive controller is designed to optimize the fuel cell system performance. As described in chapter (3), the PEM fuel cell system net power output can be maximized by maintaining the air supply pressure ratio at the optimum level for the defined fuel cell UAV mission current. When the fuel cell current is varied, the inlet air flow rate and the air pressure need to be automatically changed in order to maintain the required oxygen concentration. The proposed adaptive controller has resulted in adapting the actual compressor power to the optimum value which is obtained from a reference model. As a result, the fuel cell produces maximum net power output for the different propulsion current requirements.

In the proposed control architecture, the air supply system compressor motor voltage is regulated to the optimum value by minimizing the power error between the reference model and the actual fuel cell system. The optimum pressure which minimizes the fuel cell internal losses is estimated in the referenced model based on equation (3.45). The adaptive neuro fuzzy based inference system (ANFIS) is designed to adapt the actual compressor power with respect to the reference value.

7. FUEL CELL CONTROL AND POWER MANAGEMENT

The ISR mission (I) which described in case study (1) in the previous chapter is simulated to identify the performances of the proposed adaptive control system. The development stages of the ANFIS control architecture is described in the following sections.

7.1 Fuel Cell System Control Approaches

The majority of fuel cell control algorithms are developed to optimize the energy utilization of the fuel cell system. In contrast to the battery system, the fuel cell system converts the energy as long as the reactants are supplied. Therefore, the control of the fuel cell system input power is as important as the control of the output power of the fuel cell system. The control of input power results in minimizing the voltage losses thus increasing the fuel cell system net power output. Maintenance of the fuel cell input reactants at appropriate levels in order to minimize the concentration loss is a significant control challenge and the various control methodologies have been developed for this purpose. In the fuel cell literature, the linear control approaches such as PI and PID controllers and the advanced control methodologies such as fuzzy logic, neural networks, optimal control, adaptive control and genetic algorithm are mostly used to control the fuel cell reactants. However, in dynamic systems, the applicability of the control methodology is mainly focusing towards improving the limitations such as gain, overshoot and time response of the system. In control aspects, the feedback loops that sense the system outputs create the closed-loop control architecture and consequently response to the system variations. The closed-loop control systems normally show the advantage over the open loop systems in terms of stability. Furthermore, researchers have developed [43][44] rule base control methods which offer the advantage of training and learning algorithms thus sustaining the fuel cell performance and operational efficiency. The advanced control architecture with online learning and training algorithms give considerable benefits in dynamic system which requires a wide operational range. The adaptive controller which can learn from the system output and trains the actual system parameters to achieve desired target or referenced function has a great potential to be applied in real time system which requires an optimized power output. The ANFIS control method is the selected control approach for the fuel cell system. Alternative control methodologies are also discussed in order to appreciate

the advantages and disadvantages of them. The adaptive neuro fuzzy inference system (ANFIS) controller shows similar characteristics in terms of nonlinear adaptability for the unknown referenced model. The following sections include the various control architectures for the fuel cell air supplying system control.

- Feedforward Control Approach :

If the feedforward controller is introduced to control the compressor power, the input variable is the compressor voltage (V_{cm}), and the disturbance is the fuel cell current (I_{fc}) and lastly the performance variable is the compressor power (P_{com}). In the feedforward controller, the control signal V_{cm} affects the performance variable P_{com} through the dynamics associated with the compressor motor and the compressor inertia. However, in the open loop system, the disturbance rejection capability is moderate and hence fuel cell current variation adversely affects the performance variable P_{com} . Therefore, the absence of the feedback loop from the plant which is actual P_{com} , the feedforward controller performance is interrupted by the disturbances and thus the controller does not guarantee the expected outcomes from the fuel cell system.

- Feedback Control Approach

The feedback controllers have advantages over feedforward control in terms of the system robustness for the disturbances and for the plant parameter variations. For the fuel cell control application, a PI or a PID controller has capabilities to regulate the operating power of the compressor. In the PID control architecture, as the desired value, the reference model optimum compressor value can be used to compare with the actual compressor power. However, the reference model optimum compressor power output is a function of the fuel cell current which has nonlinear characteristics. Therefore, including the derivative part of the controller can be compromised due to the results in rapid changes and discontinuities.

A proportional and integral (PI) controller can be developed to reach the target by minimizing the error. However, the PI controller performance does not guarantee the optimal output or stability of the system due to the unknown disturbances or the modelling error and hence reduces the system robustness. Therefore, in

7. FUEL CELL CONTROL AND POWER MANAGEMENT

most feedback control systems, Observer based controllers are developed by linearizing the static feedforward model at a nominal point. In the Observer based design, the weighting factor of the performance variable (P_{com}) is depended on the target value which is the optimum compressor power. If the fuel cell current variation (range) is high, the weighing factor need to be increased. However, the increase in the weighting factor of the controller results the slow transient response and takes longer time to settle. At this stage, the oxygen starvation can not be prevented and hence fuel cell performances will be degraded. For the fuel cell air supplying system controller, the controller response time should not be an independent parameter and needs be controlled with in the fuel cell reaction time.

- Gain Scheduling Control Approach

A gain scheduling controller is another potential controller for the fuel cell air supplying system. In the gain scheduling method, the gain of the PID controller is defined based on the process variable operational span. When the process variable is entered into the new operating range, the controller updates with a predetermined set of tuning parameters designed to optimize the closed-loop performance in that range. The main advantage of the gain scheduling controller is that the developer can define any number of operational ranges to tune the controller based on the process variable. In the fuel cell control application, the optimum compressor power is the desired target and the fuel cell current is the process variable. The feedback signal is the actual compressor power. When the fuel cell current is changed, the controller desired target also changed thus resulting the gain scheduler to operate in new operational range. However, if the fuel cell current variation frequency is high, the gain scheduler also varies frequently and hence the compressor operating power also changes rapidly. The sudden changes in the compressor power result the inefficient operation of the compressor.

- ANFIS Control Approach

The ANFIS controller has more benefits than the other types of controller such as feedforward, PI, PID and Gain scheduling for the fuel cell control application. The ANFIS method combines linguistic 'if then' rules with the adaptation process

result in a controller which has the capability to adapt to the plant changes. As the main objective of the controller, the fuel cell air supplying system should be controlled as a function of fuel cell load current variation. However, the fuel cell current is an independent performance variable from the plant and has nonlinear characteristics. In order to control the air supplying system, the fuel cell current and the battery state of charge are necessary to decide the operating power of the compressor. For this scenario, the possible compressor motor voltage variations with the fuel cell current and the battery SoC can be represented by using the linguistic rule base system. However, the optimality of the fuzzy output can not be guaranteed based on the fuzzy rules defined by the expert. Therefore, an optimization methodology need to be incorporated in to the fuzzy output in order to obtain the optimized output from the fuzzy controller.

The ANFIS controller has the potential characteristics for the control of fuel cell air supplying system. In the ANFIS controller, the rule base is defined for the compressor motor voltage based on the fuel cell current and the battery SoC. The controller optimality is achieved by including the optimal reference model to adapt the actual value with the optimum. When the fuel cell current and/or battery SoC are changed, the fuzzy output is generated by the relevant fuzzy rule. Then, based on the actual compressor power and the optimum power, the error is generated and changes the fuzzy output to achieve optimum value. A main advantage of the ANFIS controller is the operating characteristics as a nonlinear system identifier. The controller output is adapted to the optimum value which has nonlinear characteristics. In addition, the controller adaptation time frequency can be controlled by changing the training step duration. Hence, the controller output does not change suddenly similar to the fuel cell current variations. Due to the training process, the ANFIS output is gradually and progressively responding to the fuel cell system variations thus resulting in an efficient operation of the fuel cell compressor. Another advantage of the ANFIS controller is the initial conditions for the controller are defined by the rule base system (linguistic) at the starting point. The proposed ANFIS controller is a combined control architecture with the optimizing and the regulating objectives.

7.2 Adaptive Control Strategy

The fuel cell air supply system should maintain the optimum compressor power to maximize the fuel cell system net power output during the UAV mission. In the ANFIS control architecture, the optimum compressor power which is described in equation (3.45) is implemented as the referenced model. The controller tracks the optimum value in each training step and changes the controller output signal to regulate the actual compressor operating power to the reference optimum value. The schematic diagram of the adaptive controller and the plant is shown in (7.1).

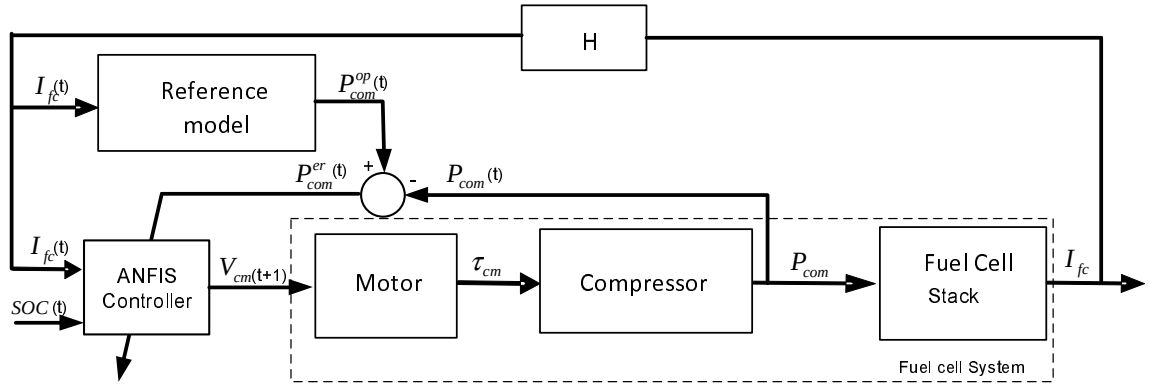


Figure 7.1: Simplified schematic diagram of the ANFIS controller and the Plant at time (t) and (t+1)

Initially, the fuzzy logic rule base determines the air supplying system compressor motor voltage. The rule base with the fuzzy rules decides the operating compressor motor voltage based on the battery state of charge SoC and the fuel cell current I_{fc} . In the ANFIS controller, the error between the actual compressor power and the optimum compressor power is minimized by using the error minimization algorithm. The back-propagation algorithm trains the fuzzy rules to achieve the ANFIS controller output to the optimum value based on the reference model. The fuzzy rule training process is a step feedback system which adapts the actual compressor power to optimum value in each training stage by controlling the compressor motor voltage (V_{cm}).

The compressor motor torque (τ_{cm}) is obtained in the compressor motor model, by considering the motor equations. In the compressor model, the dynamic behavior of the compressor speed (ω_{cm}) is determined based on the compressor inertia (J_{cp}), compressor torque τ_{cp} and the motor torque (τ_{cm}). The compressor pressure map is used

to obtain the pressure ratios for the different flow rates. Furthermore, the actual compressor power (P_{com}) is determined based on the relationship between the flow rate, pressure ratio and the compressure torque. The actual compressor power (P_{com}) is received as the feedback signal to the controller. In the ANFIS controller, the reference optimum value and the actual value is compared and the fuzzy output is trained to achieve the optimum value. The compressor and motor models will be discussed in Section (1.4) in this chapter.

7.3 ANFIS Controller Operation

The ANFIS controller modifies the fuzzy logic output based on the reference model which is developed for achieving the optimum performances. Therefore, the fuzzy rules are dynamically changed by the back propagation training algorithm to achieve the optimum value based on the reference model. After identifying the initial conditions of the compressor motor voltage, the ANFIS controller starts an online training process to adapt and consequently change the operating voltage of the compressor motor.

The layered fuzzification structure which is developed with the neural network feedback loops trains the fuzzy output by using the back-propagation algorithm and the error minimization algorithm. The process of the ANFIS controller can be described as follows:

- The optimum compressor power is determined continuously as a function of the fuel cell current.
- The error minimization algorithm produces the error between the actual output and the reference model.
- The back-propagation algorithm changes the fuzzy rule's mean and variance until the ANFIS controller adapts to the optimum value.
- The online learning and training processes continue until the controller changes the actual power output of the compressor to the optimum value.

7. FUEL CELL CONTROL AND POWER MANAGEMENT

Figure (7.2) shows the network representation of the ANFIS. The back-propagation algorithm trains the compressor motor voltage (V_{cm}) based on the error between the optimum compressor power value (P_{com}^{op}) and the actual compressor power value (P_{com}). The compressor motor voltage (V_{cm}) is the defuzzified output of the ANFIS.

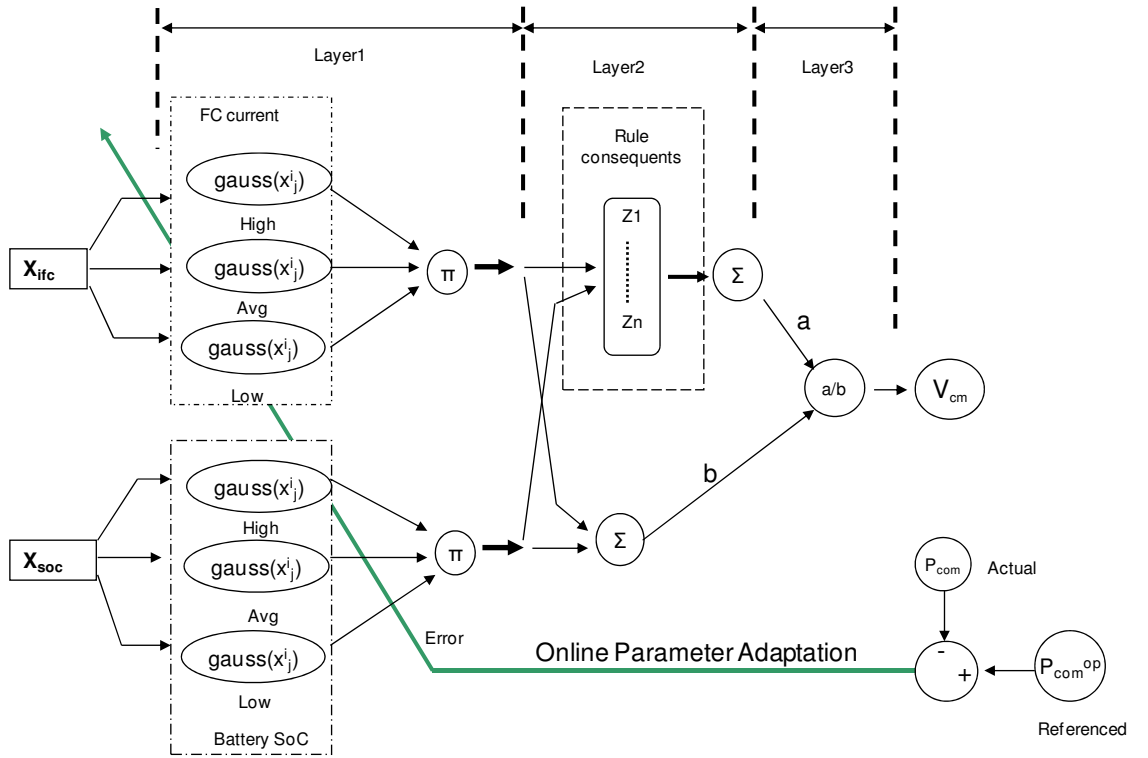


Figure 7.2: Network representation of the adaptive neuro fuzzy inference system

Equation (7.7) shows, at the training step $(t + 1)$, the fuzzy output $Z(t + 1)$ is generated by the difference between the previous fuzzy output $Z(t)$ and the error between the optimum compressor power at step $(t + 1)$ in the reference model and the actual compressor power.

At the training step (t) , the fuel cell current is $I_{fc}(t)$ and the optimum pressure is $P_{com}^{op}(t)$. At this stage, the ANFIS output is step behind as $V_{cm}(t - 1)$ (or at initial conditions at starting point). Then the error is generated as $e(t)$ and trains the fuzzy

rules to achieve the optimum value which is $V_{cm}(t - 1) = V_{cm}(t)$. In the next step $(t + 1)$, the fuel cell current I_{fc} which is a function of the load has been changed and new value is $I_{fc}(t + 1)$. Then, the reference model generates the new $P_{com}^{op}(t + 1)$ and compares with the $P_{com}(t)$ value which is still the acting power of the compressor a step behind. After training, $V_{cm}(t) = V_{cm}(t + 1)$. The duration between the step $(t-1)$, (t) and $(t+1)$ is defined not to exceed the fuel cell maximum transient response time which is considered as 2 seconds.

7.3.1 Fuzzy Logic Decisions

The air supply system control decisions are included in the fuzzy logic rule base to decide the fuel cell system compressor motor voltage. The fuzzy controller input parameters are the fuel cell current (I_{fc}) and the battery SoC . The fuzzy logic membership functions are defined based on the linguistics rules developed by considering the dynamic behavior of the hybrid system. The ANFIS controller inputs such as I_{fc} , SoC , P_{com} , P_{com}^{op} and the fuzzy output Z are normalized between 0 and 1. The fuzzy logic system is consisted of four different layers called fuzzification interface, fuzzy rule base, fuzzy inference machine and defuzzification interface.

7.3.1.1 Fuzzification Interface

In multi inputs and single output Sugeno type fuzzy inference system, the battery SoC is divided into three different status called battery $SoC(low)$, battery $SoC(avg)$ ¹ and battery $SoC(high)$. Similarly, the fuel cell current I_{fc} is assigned into three regions $I_{fc(high)}$, $I_{fc(avg)}$ and $I_{fc(low)}$. The non-fuzzy input space is mapped into the fuzzy set $U \subset R^n$ where U is the fuzzy set characterized by membership functions $\mu_{(SoC)}$ and $\mu_{I_{fc}} : U \rightarrow [0, 1]$. Gaussian membership functions are selected to represent the battery SoC and the I_{fc} characteristics as shown in (7.1) [41]. Define, $x_i = [x_1, x_2] = [SoC, I_{fc}]$

$$\mu_{A_i^j}(x_i) = a_j^i \exp \left\{ -\frac{1}{2} \left(\frac{x_i - \bar{x}_j^i}{\sigma_j^i} \right)^2 \right\} \quad (7.1)$$

¹ battery $SoC(avg)$: Average level of the battery SoC

7. FUEL CELL CONTROL AND POWER MANAGEMENT

α_i^j is a constant $0 < \alpha_i^j \leq 1$ where j is the number of rules ($j = 1, 2, \dots, M$) and i is the number of fuzzy inputs ($i = 1, 2, \dots, n$). Mean and variance of the Gaussian function are represented by $\bar{x}_i^j$ and σ_i^j respectively. Figures (7.3) and (7.5) show the battery SoC and the I_{fc} membership functions.

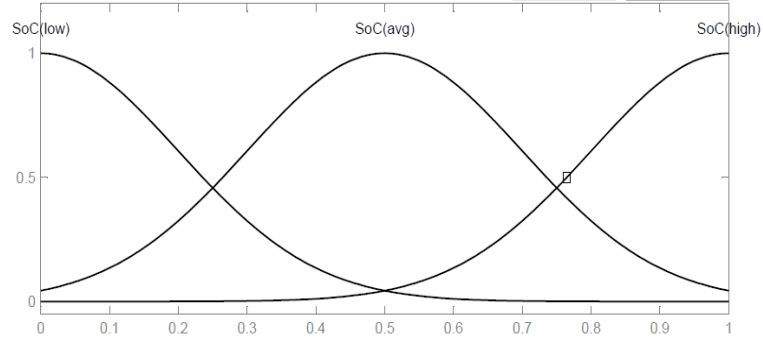


Figure 7.3: Normalized Battery SoC input membership functions

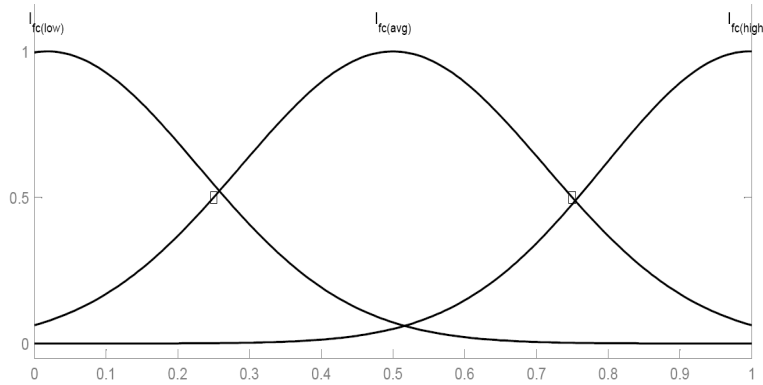


Figure 7.4: Normalized fuel cell current (I_{fc}) input membership functions

In the Sugeno type fuzzy set, the output V_{cm} is defined in three constant voltages; $V_{cm}(low) = 0.25$, $V_{cm}(avg) = 0.5$ and $V_{cm}(high) = 0.8$.

7.3.1.2 Rule Base System

The fuzzy rule based is a set of linguistic rules defined with IF-THEN conditions. The rule base which has M number of rules M ; $j = 1, 2, \dots, M$ can be expressed as shown in

Table 7.1: Rule based system

	$SoC(low)$	$SoC(avg)$	$SoC(high)$
$I_{fc}(low)$	avg	low	low
$I_{fc}(avg)$	$high$	avg	low
$I_{fc}(high)$	$high$	$high$	avg

(7.2). The fuzzy output is denoted as Z .

$$\begin{aligned}
 R^j : & \text{ IF } x_1 \text{ is } A_1^j \text{ and } x_2 \text{ is } A_2^j \text{ and...and } x_n \text{ is } A_n^j \\
 & \text{ THEN } Z^j \text{ is } B^j
 \end{aligned} \tag{7.2}$$

$x_i; i = 1, 2, \dots, n$ are the fuzzy system input parameters. The membership functions $\mu_{SoC_i^j}(x_i)$ and $\mu_{I_{fc}_i^j}(x_i)$ are represented the input linguistic term A_i^j . B^j is the linguistic term for the fuzzy output. Equation (7.3) shows the first rule assigned to the rule base system.

$$R^1 : \text{ IF } x_1 \text{ is } \mu_{SoC(low)} \text{ and } x_2 \text{ is } \mu_{I_{fc}(low)} \text{ THEN } Z \text{ is } avg \tag{7.3}$$

If the battery SoC and the I_{fc} are in low modes , then the compressor motor voltage is average mode $V_{cm}(avg)$ mode. Table (7.4) shows the rule base developed for this application.

7.3.1.3 Fuzzy Inference Machine

The fuzzy inference machine is a decision making logic which converts the fuzzy rule base into the fuzzy output. The battery SoC and the I_{fc} input values are converted to the fuzzy output Z based on the rules defined in the rule base system.

7. FUEL CELL CONTROL AND POWER MANAGEMENT

7.3.1.4 Defuzzification Interface

In defuzzification stage, the fuzzy output value in the fuzzy inference machine is converted into a non fuzzy value (real number). The compressor motor voltage is obtained by centroid defuzzification method as shown in (7.4) [41].

$$V_{cm} = f(t) = \frac{\sum_{j=1}^M \bar{Z}^j (\prod_{i=1}^n \mu_{A_i^j}(x_i))}{\sum_{j=1}^M (\prod_{i=1}^n \mu_{A_i^j}(x_i))} \quad (7.4)$$

$\bar{Z}^j$ is the fuzzy output of each rule. The fuzzy surface generated by the rule base system is shown in figure(7.5).

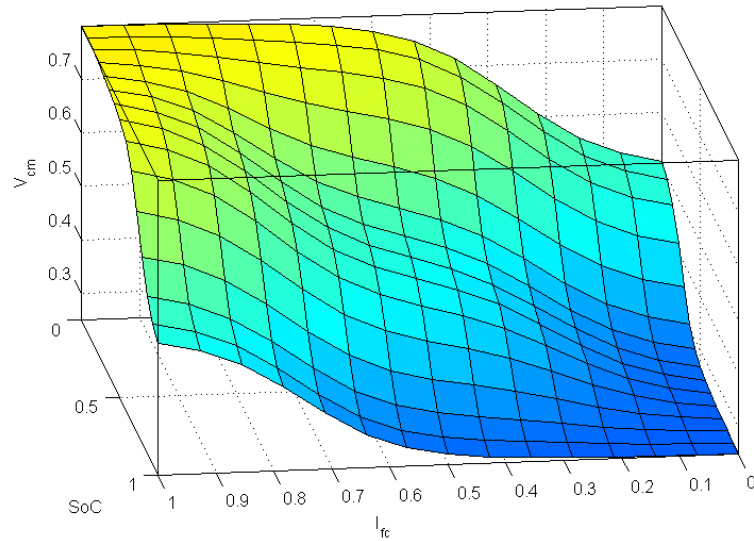


Figure 7.5: Non-trained fuzzy surface generated by the rule base (initial)

7.3.2 Adaptive Process

The adaptation process continues dynamically and online by changing the Gaussian equation estimation parameters $\bar{x}_i$ and σ_i^j in input membership functions and the fuzzy output $\bar{Z}^j$. The error minimization of the actual compressor power (P_{com}) and the

optimum compressor power (P_{com}^{op}) is shown in equation (7.5).

$$e(t) = \frac{1}{2}[P_{com}^{op}(t+1) - P_{com}(t)]^2 \quad (7.5)$$

$$e(t) = \frac{1}{2}[P_{com}^* - P_{com}]^2 \quad (7.6)$$

$$Define : P_{com}^* \triangleq P_{com}^{op}$$

Let us consider, the fuzzy system has only M number of rules and unit membership value $a_j^i = 1$. The remaining estimation parameters, $x_i^j(t)$, $\sigma_i^j(t)$ and $\bar{Z}^j(t)$ are updated at each time step to achieve the desired V_{cm} . The fuzzy output of the next time step $\bar{Z}^j(t+1)$ is determined by subtracting the rate of error change ($\frac{\partial e}{\partial \bar{Z}^j}$) from the existing $\bar{Z}^j(t)$ as shown in (7.7) [41]. The fuzzy output of the rule base $Z(t)$ becomes $\bar{Z}(t)$ after the training process.

$$\bar{Z}^j(t+1) = \bar{Z}^j(t) - \alpha \frac{\partial e}{\partial \bar{Z}^j} \quad (7.7)$$

$t = 1, 2, \dots$, and α is a constant step size. The fuzzification interfaces derived in (7.4) can be expressed as shown in equations (7.8), (7.9) and (7.10). Therefore, the V_{cm} can be represented by a and b as shown in (7.11).

$$y^j = \prod_{i=1}^n \mu_{A_i^j}(x_i) \quad (7.8)$$

$$b = \sum_{j=1}^M y^j \quad (7.9)$$

$$a = \sum_{j=1}^M (\bar{Z}^j y^j) \quad (7.10)$$

$$V_{cm} = \frac{a}{b} \quad (7.11)$$

7. FUEL CELL CONTROL AND POWER MANAGEMENT

By applying the chain rule into (7.5),

$$\frac{\partial e}{\partial \bar{Z}^j} = (P_{com}^* - P_{com})\alpha \frac{\partial P_{com}}{\partial a} \frac{\partial a}{\partial \bar{Z}^j} \quad (7.12)$$

However, the actual ANFIS system output is the compressor electric motor voltage V_{cm} . Hence, term $\left(\frac{\partial P_{com}}{\partial a} \frac{\partial a}{\partial \bar{Z}^j}\right)$ is not compatible to the proposed ANFIS architecture. Therefore, we define q , a conversion factor which results in equation (7.13).

$$\frac{\partial P_{com}}{\partial a} \frac{\partial a}{\partial \bar{Z}^j} = q \cdot \frac{\partial V_{cm}}{\partial a} \frac{\partial a}{\partial \bar{Z}^j} \quad (7.13)$$

Term q normalizes P_{com} between 0 and 1 to represent the variation of the V_{cm} for the ANFIS controller error minimization process. Hence, the equation (7.12) is represented as,

$$\frac{\partial e}{\partial \bar{Z}^j} = (P_{com}^* - P_{com})\alpha \frac{\partial [q \cdot V_{cm}]}{\partial a} \frac{\partial a}{\partial \bar{Z}^j} \quad (7.14)$$

$$\frac{\partial e}{\partial \bar{Z}^j} = (P_{com}^* - P_{com})(\alpha \cdot q) \frac{\partial V_{cm}}{\partial a} \frac{\partial a}{\partial \bar{Z}^j} \quad (7.15)$$

$$\frac{\partial e}{\partial \bar{Z}^j} = (\alpha \cdot q)(P_{com}^* - P_{com}) \frac{1}{b} y^j \quad (7.16)$$

Equation (7.16) substitutes into the equation (7.7) and the updated fuzzy output is shown in (7.17) [41].

$$\bar{Z}^j(t+1) = \bar{Z}^j(t) - \alpha \cdot q \left(\frac{P_{com}^* - P_{com}}{b} \right) y^j \quad (7.17)$$

$$\therefore V_{cm}(t+1) = V_{cm}(t) - \alpha \cdot q \left(\frac{P_{com}^* - P_{com}}{b} \right) y^j \quad (7.18)$$

For the consideration of error minimization, term K_1 is define to represent the error $\alpha \cdot q \left(\frac{P_{com}^* - P_{com}}{b} \right) y^i$. Hence, the equation (7.18) can be shown as follows:

$$V_{cm}(t+1) = V_{cm}(t) - K_1 \quad (7.19)$$

The following conditions should satisfy during the adaptation and after the adaptation in order to reach the zero error.

- If the ANFISS is adapting, then $K_1 \neq 0$, Hence, If $K_1 \neq 0 \Rightarrow P_{com}^* \neq P_{com}$ and Other parameters $\neq 0$
- If the ANFISS is adapted, then $K_1 = 0$, Hence, If $K_1 = 0 \Rightarrow P_{com}^* = P_{com}$ and Other parameters $\neq 0$

The ANFIS controller updated mean ($\bar{x}$) is shown in (8.37),(7.21) and (7.23) [41].

$$\bar{x}_i^j(t+1) = \bar{x}_i^j(t) - \alpha \frac{\partial e}{\partial \bar{x}_i^j} \quad (7.20)$$

$$\frac{\partial e}{\partial \bar{x}_i^j} = \alpha(P_{com}^* - P_{com}) \frac{\partial P_{com}}{\partial y^j} \frac{\partial y^j}{\partial \bar{x}_i^j} \quad (7.21)$$

$$\frac{\partial e}{\partial \bar{x}_i^j} = \alpha(P_{com}^* - P_{com}) \frac{\partial [q.V_{cm}]}{\partial y^j} \frac{\partial y^j}{\partial \bar{x}_i^j} \quad (7.22)$$

$$\bar{x}_i^j(t+1) = \bar{x}_i^j(t) - (\alpha.q) \left(\frac{P_{com}^* - P_{com}}{b} \right) (\bar{Z}^j - P_{com}) \left(y^j \frac{x_i^j - \bar{x}_i^j(t)}{\sigma_i^{j2}(t)} \right) \quad (7.23)$$

The variance (σ_i^j) of the gaussian function (7.4) is changed with the error generated by (7.5). The updated variance can be represented as shown in (7.25) [41].

$$\sigma_i^j(t+1) = \sigma_i^j(t) - \alpha \frac{\partial e}{\partial \sigma_i^j} \quad (7.24)$$

$$\sigma_i^j(t+1) = \sigma_i^j(t) - (\alpha.q) \left(\frac{P_{com}^* - P_{com}}{b} \right) (\bar{Z}^j - P_{com}) \left(\frac{(x_i - \bar{x}_i^j(t))^2}{\sigma_i^{j3}(t)} \right) \quad (7.25)$$

The updated versions of the estimation parameters, $\bar{Z}_i^j$, $\bar{x}_i^j$ and σ_i^j are shown in (7.17),(7.23) and (7.25).

7. FUEL CELL CONTROL AND POWER MANAGEMENT

7.3.3 ANFIS MATLAB Model

The ANFIS controller which is shown in figure (7.6) consists of four inputs for the reference optimum power, actual compressor power, fuel cell current and for the battery SoC. V_{cm} is the output of the controller. In the fuzzy logic controller section, the rule base is defined with the membership functions. The each membership function has variable mean and variance. The updated versions of the mean and variance are received from the trainers as the feedback signals for the fuzzy logic controller. The following steps show the programme developed for the fuzzy controller.

```
Function1 [b,f,y1,y2,y3,y4,y5,y6,r = fuzzy1(lfc,soc,z1,z2,z3,z4,z5,z6,z7,z8,z9,  
m1,m2,m3,m4,m5,m6,v1,v2,v3,v4,v5,v6)  
p=lfc(1,1);  
a=soc(1,1);
```

Input membership function

```
Ifl = exp(-((p - m1)/v1)2);  
Ifa = exp(-((p - m2)/v2)2);  
Ifh = exp(-((p - m3)/v3)2);  
scl = exp(-((a - m4)/v4)2);  
sca = exp(-((a - m5)/v5)2);  
sch = exp(-((a - m6)/v6)2);
```

Rules

```
r1=scl*Ifl;  
r2=scl*Ifa;  
r3=scl*Ifh;  
r4=sca*Ifl;  
r5=sca*Ifa;  
r6=sca*Ifh;  
r7=sch*Ifl;  
r8=sch*Ifa;  
r9=sch*Ifh;
```

Denominator

$$b=(r1+r2+r3+r4+r5+r6+r7+r8+r9);$$

$$h1=r1*z1;$$

$$h2=r2*z2;$$

$$h3=r3*z3;$$

$$h4=r4*z4;$$

$$h5=r5*z5;$$

$$h6=r6*z6;$$

$$h7=r7*z7;$$

$$h8=r8*z8;$$

$$h9=r9*z9;$$

Numerator

$$\text{num} = h1+h2+h3+h4+h5+h6+h7+h8+h9;$$

Defuzzification

$$f=(\text{num}/b);$$

outputs

$$y1=r1;$$

$$y2=r2;$$

$$y3=r3;$$

$$y4=r4;$$

$$y5=r5;$$

$$y6=r6;$$

$$r=[r1,r2,r3,r4,r5,r6,r7,r8,r9];]$$

End{function1}

Z – Trainer which is the fuzzy output trainer generates the fuzzy output for each rule by comparing the actual and the optimum pressures values. *Mean – Trainer* and *Variance – Trainer* generate the new variance and mean for the I_{fc} and the SoC membership functions. The equations (7.17),(7.23) and (7.25) were developed in the *Z – Trainer*, *Mean – Trainer* and *Variance – Trainer* models respectively.

7. FUEL CELL CONTROL AND POWER MANAGEMENT

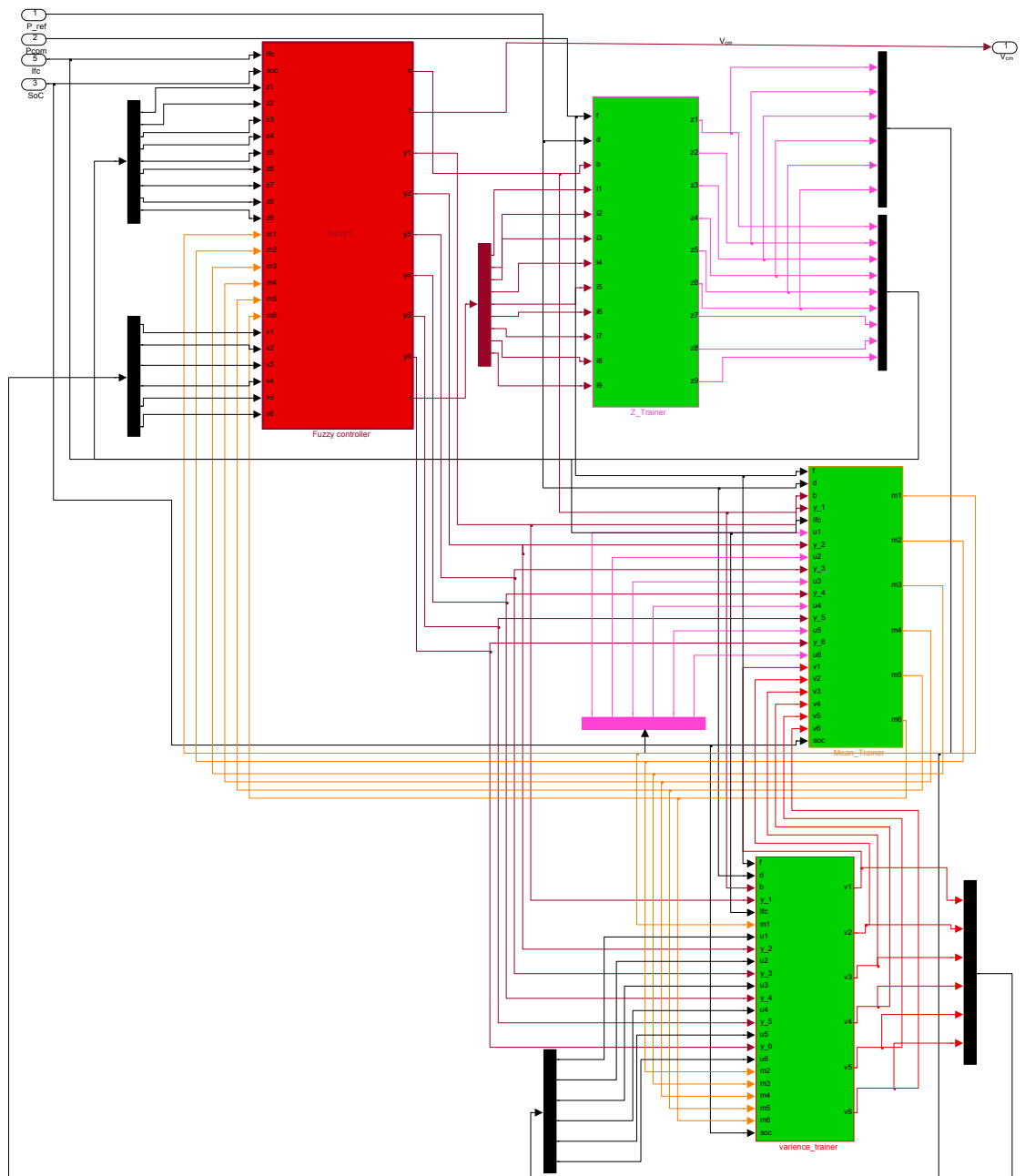


Figure 7.6: ANFIS controller

7.4 Compressor and Motor Models

The compressor and the motor models are developed in Simulink to validate the ANFIS controller performances. The schematic diagram of the simulation architecture with the ANFIS controller, the compressor, the motor and the fuel cell models are shown in figure (7.7).

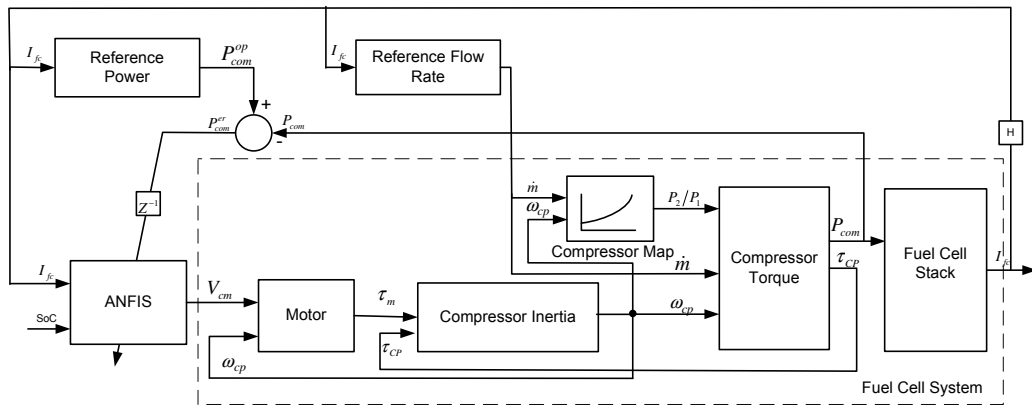


Figure 7.7: Compressor and motor models with ANFIS controller

The motor torque (τ_{cm}) is obtained from the equation (7.26) by considering the motor mechanical efficiency $\eta_{cm} = 92\%$ and the motor speed (ω_{cp}).

$$\tau_{cm} = \eta_{cm} \frac{k_{ct}}{R_{cm}} (V_{cm} - k_{cv} \omega_{cp}) \quad (7.26)$$

τ_{cm} is the compressor motor torque input (Nm) and ω_{cp} is the compressor speed in (rad/sec). The selected DC motor specifications such as the voltage constant $k_{cv} = 0.0344V/(rad/sec)$ and motor resistance $R_{cm} = 3.5\Omega$ are obtained from the commercially available motor. $k_{ct} = 1.64Nm/A$ is the motor torque constant. The maximum operating speed of the motor is 9000rpm. The motor nominal voltage is 24V.

The compressor inertia model shows the relationship between the motor torque, the compressor torque and the compressor acceleration. From the equation (7.27), the

7. FUEL CELL CONTROL AND POWER MANAGEMENT

speed of the compressor is obtained by integrating the torque difference.

$$J_{cp} \frac{d\omega_{cp}}{dt} = (\tau_{cm} - \tau_{cp}) \quad (7.27)$$

J_{cp} is the compressor and motor inertia 0.00005 kg/m^2 . Initial condition of the motor speed is considered as 750 rpm . In the compressor torque model, the relationship between the pressure ratio $(\frac{Pr_2}{Pr_1})$, the air mass flow rate $(\dot{m})$ rate, the compressor speed and the compressor torque (τ_{cp}) is obtained[6].

$$\tau_{cp} = \frac{c_p}{\omega_{cp}} \frac{T}{\eta_{cp}} \left[\left(\frac{Pr_2}{Pr_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \dot{m}_{air} \quad (7.28)$$

The required air mass flow rate $(\dot{m}_{air})$ is determined based on the equation (3.38) in the chapter (3). The derivation shows that the air mass flow rate is a function of the fuel cell current as shown in equation (7.29).

$$\dot{m}_{air} = 3.57 \times 10^{-7} \lambda n i_{fc} \quad (7.29)$$

$n = 24$ is the number of fuel cell and $\lambda = 2$ is considered for the fuel cell reaction stoichiometry.

A compressor map is used to determine the pressure ratios of the compressor for different compressor speeds and the flow rates. The *Jensen & Kristensen* method described in [74] is used to develop the compressor map.

In the compressor torque model, based on the input variables which are the air mass flow rate, the pressure ratio and the compressor speed, the compressor actual power is determined.

7.4.1 Compressor Map

Based on the *Jensen & Kristensen* method derived in [74], the compressor map is developed for the compressor flow rates versus the pressure ratio variations. The compressor

dimensionless head parameter (ψ) is defined in (7.30) [74].

$$\psi = c_p T \left[\left(\frac{Pr_2}{Pr_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] / \frac{U_c^2}{2} \quad (7.30)$$

U_c is the compressor blade tip speed (m/s). U_c is defined as:

$$U_c = \frac{\pi}{60} d_c \omega_{cp} \quad (7.31)$$

d_c is the compressor diameter (0.05m). The normalized compressor flow rate is defined in (7.32) [74].

$$\phi = \frac{\dot{m}}{\rho \frac{\pi}{4} d_c^2 U_c} \quad (7.32)$$

In the *Jensen & Kristensen* method, the normalized compressor flow rate (ϕ) and the head parameter (ψ) are represented as shown in (7.33) [6].

$$\phi = \phi_{max} \left[1 - \exp \left(\beta \left(\frac{\psi}{\psi_{max} - 1} \right) \right) \right] \quad (7.33)$$

ψ_{max} , ϕ_{max} and β are defined as the functions of the Mach number M ,

$$\phi_{max} = a_4 M^4 + a_3 M^3 + a_2 M^2 + a_1 M + a_0 \quad (7.34)$$

$$\beta = b_2 M^2 + b_1 M + b_0 \quad (7.35)$$

$$\psi_{max} = c_5 M^5 + c_4 M^4 + c_3 M^3 + c_2 M^2 + c_1 M + c_0 \quad (7.36)$$

Mach number M is defined in (7.37);

$$M = \frac{U_c}{\sqrt{\gamma R_a T}} \quad (7.37)$$

7. FUEL CELL CONTROL AND POWER MANAGEMENT

Table 7.2: Compressor Map Regression Coefficients [6]

Parameter	Value	Parameter	Value
a_4	-2.7011×10^{-5}	b_0	4.58463
a_3	2.9165×10^{-4}	c_5	-7.98622×10^{-2}
a_2	-3.5351×10^{-3}	c_4	0.76101
a_1	-4.1478×10^{-4}	c_3	-0.27286
a_0	3.6985×10^{-3}	c_2	1.96501
b_2	2.5029	c_1	0.13859
b_1	-1.6573	c_0	0.53647

R_a is the air gas constant $2.869 \times 10^2 J/(kg.K)$. T is the inlet air temperature $298.15K$. The regression coefficients a_i , b_i and c_i are obtained from [6] are shown in table (7.2). By substituting the coefficients to (8.28), (7.35) and (8.31), the ϕ_{max} , β and ψ_{max} are obtained. Based on the equations (7.30), (7.32) and (7.33), the compressor pressure ratios are determined for different flow rates. Figure (7.8) shows the compressor map

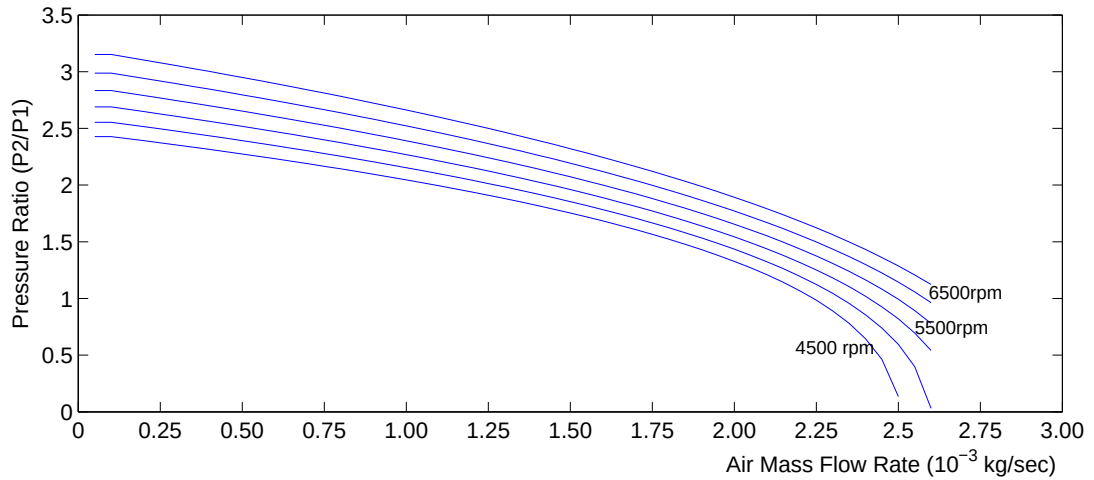


Figure 7.8: Compressor Map

7.5 Simulations

The ANFIS based air supply control architecture is simulated in Matlab Simulink to verify the proposed control methodology. The neuro-fuzzy adaptive controller, the

7. FUEL CELL CONTROL AND POWER MANAGEMENT

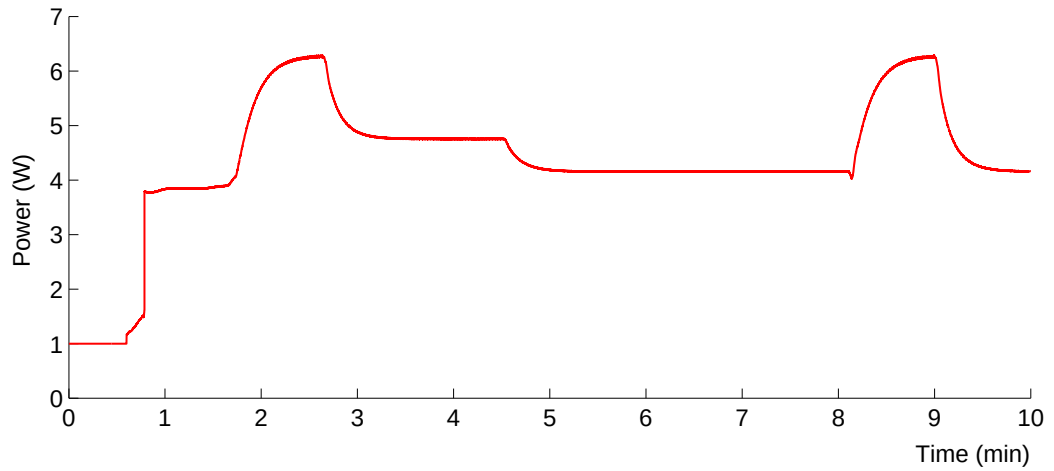


Figure 7.10: *Optimum compressor power during the mission (I)*

to 24.8V during the high power state. The motor voltage was decreased during the charging mode of the propulsion system. After 8 minutes, the motor voltage was again increased in order to accelerate the compressor speed.

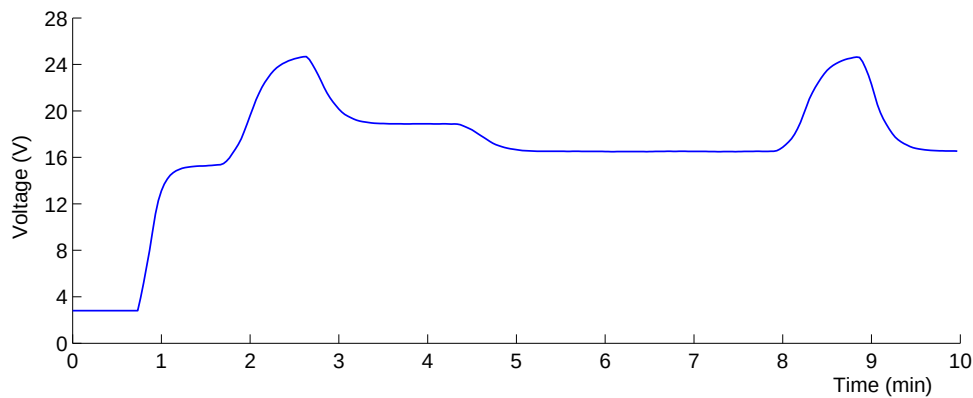


Figure 7.11: *ANFIS control signal for the compressor motor voltage variations*

The estimation parameters of the input membership functions which were trained by the error minimization algorithm changed their initial values according to the optimum compressor referenced power profile. In each time step, the mean, the variance and the fuzzy output were trained to achieve the desired target. The trained versions of the rule base during the high power state and the charging power state were considered to

show the results of the adaptive control strategy. During the charging power state, the fuel cell current membership function at 4 minutes is considered to show the ANFIS adaptation. The table (7.3) shows the changes in the mean and the variance of the fuel cell current membership functions at the initial state and at 4 minutes.

Table 7.3: Fuel cell current estimation parameters before and after training process

	$I_{fc}(low)$	$I_{fc}(avg)$	$I_{fc}(high)$
$Mean(\bar{x})$	0	0.5	1
$Trained\ Mean(\bar{x})$	0.098	0.458	0.988
$Variance(\sigma)$	0.3	0.3	0.3
$Trained\ Variance(\sigma)$	0.319	0.306	0.298

Figure (7.12) shows the changes in the fuel cell current membership function after the training process during the charging state. The shapes of the Gaussian functions have changed due to the variations of the means and the variances. At this state, the fuel cell current was varied at high stage and hence the most trained functions are the fuel cell current *low* and *avg* membership functions.

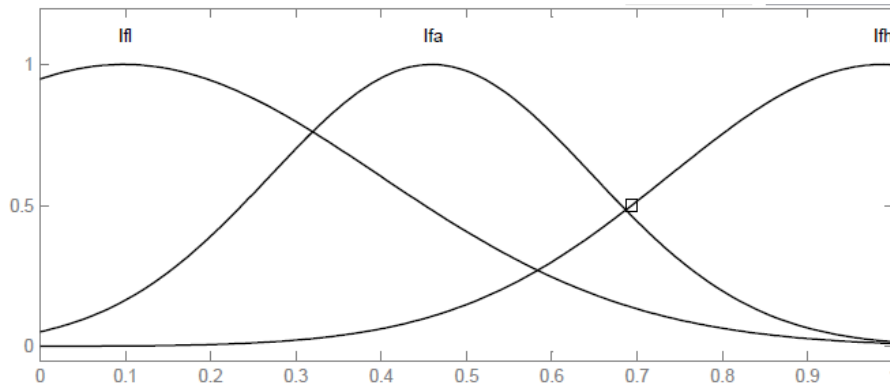


Figure 7.12: Trained fuel cell current membership functions of the ANFIS controller

Figure (7.13) shows the trained fuzzy surface during the charging state of the propulsion system. Due to the low fuel cell current and the high battery state of charge, the compressor voltage output was at an average state. The fuzzy output has been trained from average 0.5 to 0.562 after the training process at time 4 minutes.

For the high power state ANFIS operation, the battery SoC variations at 8.5 minutes was considered. The table (7.4) shows the changes in the mean and the variance of the battery SoC membership functions at the initial state and after the training process.

7. FUEL CELL CONTROL AND POWER MANAGEMENT

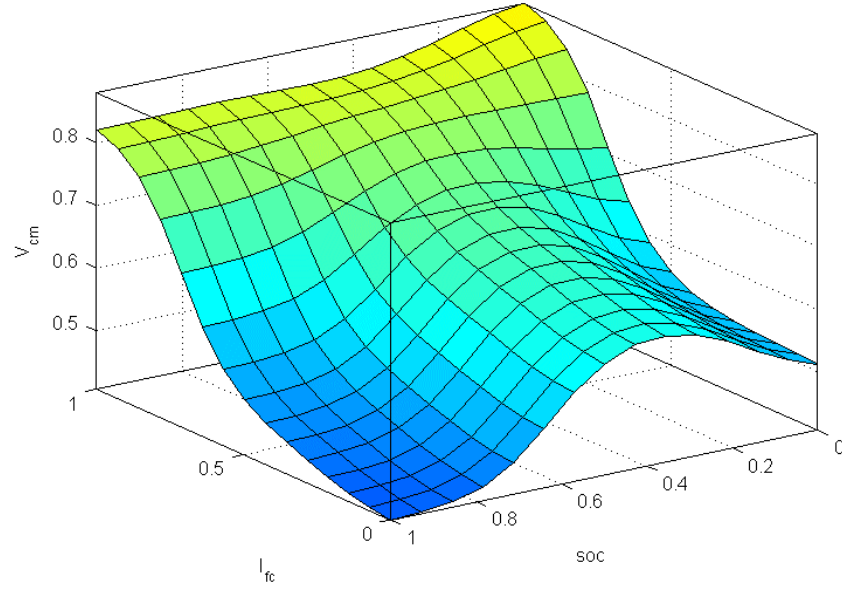


Figure 7.13: Trained ANFIS surface during the charging power state

Table 7.4: Battery SoC estimation parameters before and after training process

	<i>SoC(low)</i>	<i>SoC(avg)</i>	<i>SoC(high)</i>
$Mean(\bar{x})$	0	0.5	1
$Trained\ Mean(\bar{x})$	0.03	0.454	0.983
$Variance(\sigma)$	0.2	0.2	0.2
$Trained\ Variance(\sigma)$	0.254	0.165	0.208

The figure (7.14) shows the trained membership functions of the battery SoC during the high power state of the propulsion system. The battery SoC *high* membership function shape has changed due to the variations of the battery SoC during the high power state operation. The trained fuzzy surface at high power state at 8.5 minutes is shown in figure (7.15). The trained versions of the estimation parameters and the fuzzy surfaces proved the online adaptation process of the ANFIS based controller.

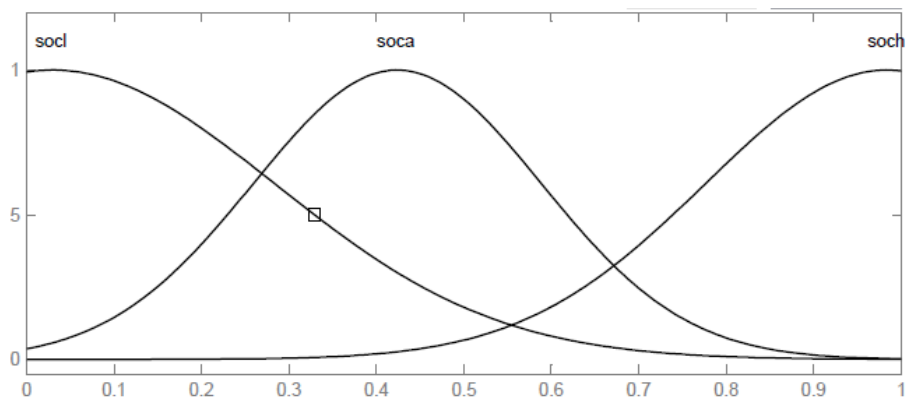


Figure 7.14: *Trained SoC membership functions of the ANFIS controller*

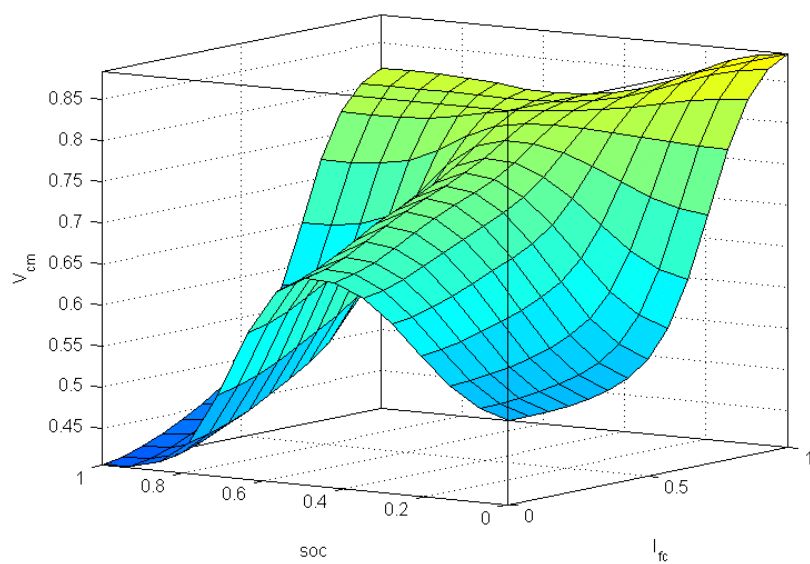


Figure 7.15: *Trained ANFIS control surface during the high power state*

7. FUEL CELL CONTROL AND POWER MANAGEMENT

7.5.2 Plant Results

The results obtained from the compressor motor, the compressor and the fuel cell are shown in this section. The figure (7.16) illustrates the compressor speed variation during the mission. The compressor speed reached to $6623rpm$ at the peak current point of the propulsion system. During the charging state, the compressor speed was $4421rpm$ after 5 minutes time period. The compressor torque τ_{cp} variation is shown in figure (7.17). The compressor torque was increased to $0.0091Nm$ at high speed operation and during the charging speed, the torque was reduced to $0.00896Nm$.

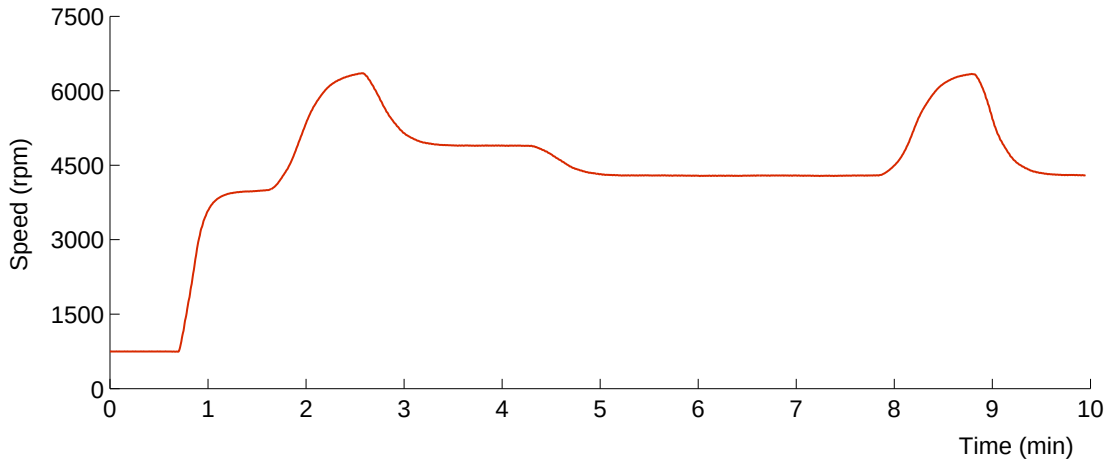


Figure 7.16: The compressor speed variation during the mission (I)

Figure (7.18) shows the required air mass flow rate during the mission. The compressor air mass flow rate was determined as a function of the fuel cell current based on the equation (3.38) which is discussed in chapter (3). When the fuel cell current was lowered, the amount of oxygen consumption was reduced and hence the required air mass flow rate also decreased. The air mass flow rate was increased during the high fuel cell current operation.

The pressure ratio of the compressor during the mission (I) was determined from the compressor map developed in section 7.4.1. The figure (7.19) shows the compressor pressure ratio variations during the mission (I). When the flow rate is increased during the high power mode, the compressor pressure ratio is reduced. During the charging and endurance power modes, the pressure ratio was increased.

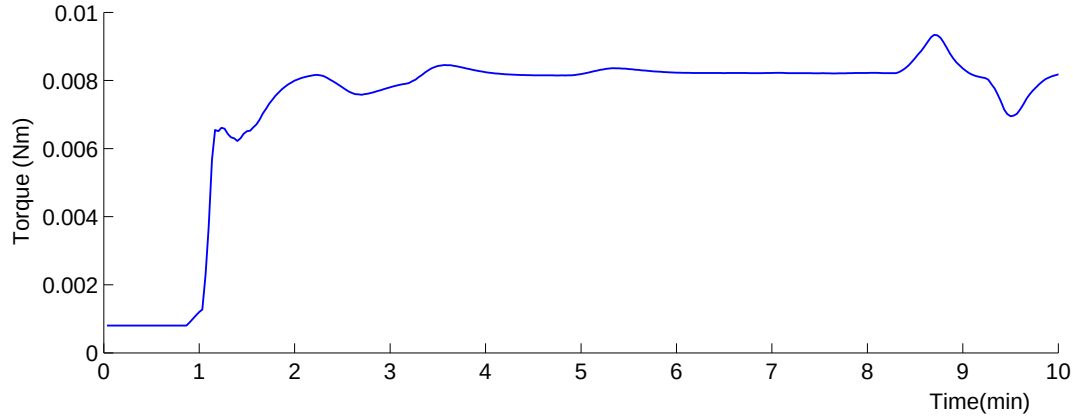


Figure 7.17: *The compressor torque variation during the mission (I)*

The actual compressor power variation is shown in figure (7.20). The compressor power varied smoothly from the low power stages to the high power stages during the mission. When the high power mode was activated, the compressor power was gradually increased to the optimum level. During the charging and endurance power states, the compressor power was changed to its optimum levels by the ANFIS controller.

Figure (7.21) shows the actual power output and the optimum compressor power variation during the mission (I). The actual power profile shows the smooth adaptation to the optimum power profile. During the startup state, the compressor increased the power up to the rated level which 3.8W. When the high power mode was activated, the optimum power obtained from the reference model was suddenly increased. However, the actual compressor power output was gradually increased by minimizing the error between the actual and the optimum power values. During the charging power mode, the compressor power was reduced and was maintained at a constant value. In each constant power operation of the compressor, the power error between the optimum and the actual power was gradually converging to zero during the adaptation.

7. FUEL CELL CONTROL AND
POWER MANAGEMENT

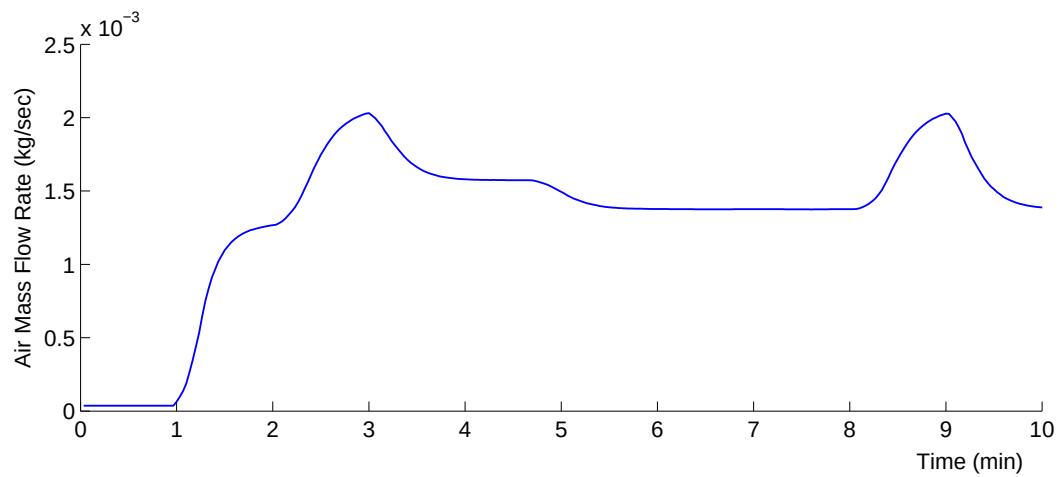


Figure 7.18: Required air mass flow rate for the mission (I)

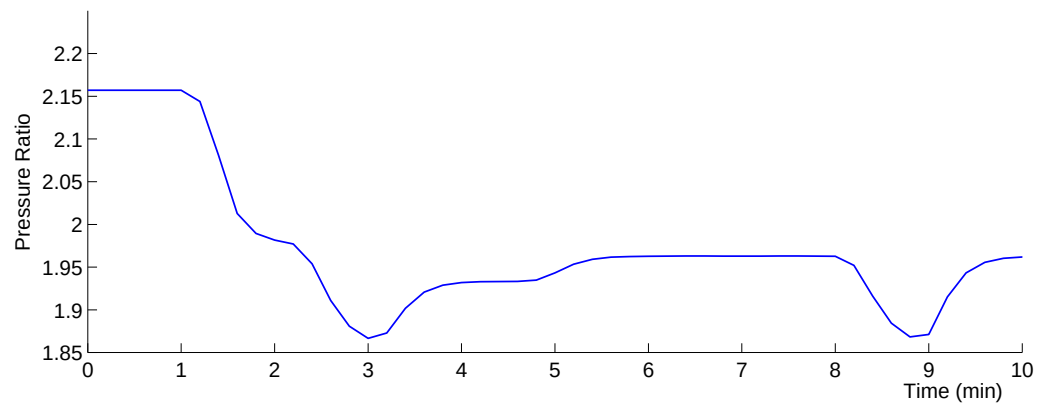


Figure 7.19: Pressure ratio variation during the mission (I)

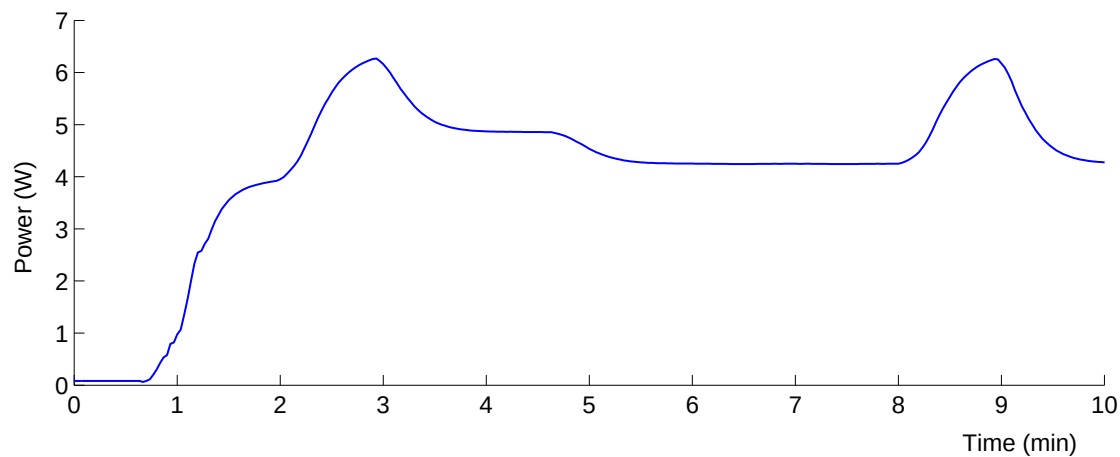


Figure 7.20: Actual compressor power (P_{com}) variation during the mission (I)

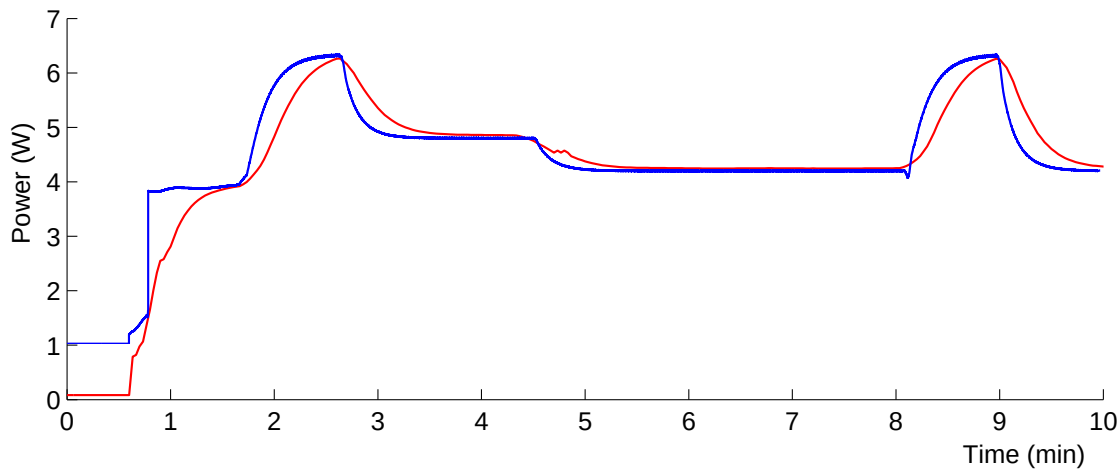


Figure 7.21: Actual compressor power adaptation to the optimum compressor power during the mission (I)

7.5.3 Compressor Power Comparison

The PEM fuel cell system performances were compared based on the optimum compressor power mode and a constant compressor power mode. The optimum compressor power configuration which gives the maximum net power output from the fuel cell stack is a load following process which shows a considerable amount of energy saving compared to the constant compressor power mode. In the constant compressor power configuration, the compressor power was maintained at 6.25W constantly which was the highest compressor power requirement throughout the mission.

Figure (7.22) shows the fuel cell system net power output during the optimum compressor power operation. The compressor operating power was dynamically changed with the fuel cell current variations. Figure (7.23) shows the fuel cell net power output during the constant power configuration. In figure (7.24), the PEM fuel cell net power outputs were compared between the constant power and the optimum power configurations. The results shows that approximately 2.62% fuel cell energy could be saved during the charging state in the optimum compressor power configuration.

These simulation results show the proposed ANFIS controller performances. As the main advantage, the controller shows smoother and progressive adaptation of the actual compressor power to the optimum compressor power P_{com}^{op} . As a result of the

7. FUEL CELL CONTROL AND

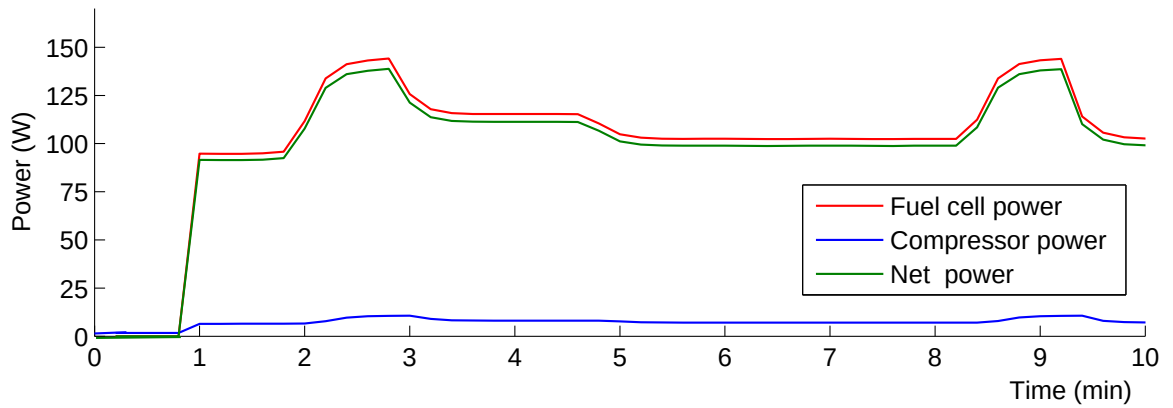


Figure 7.22: Fuel cell system net power output with the optimum compressor power

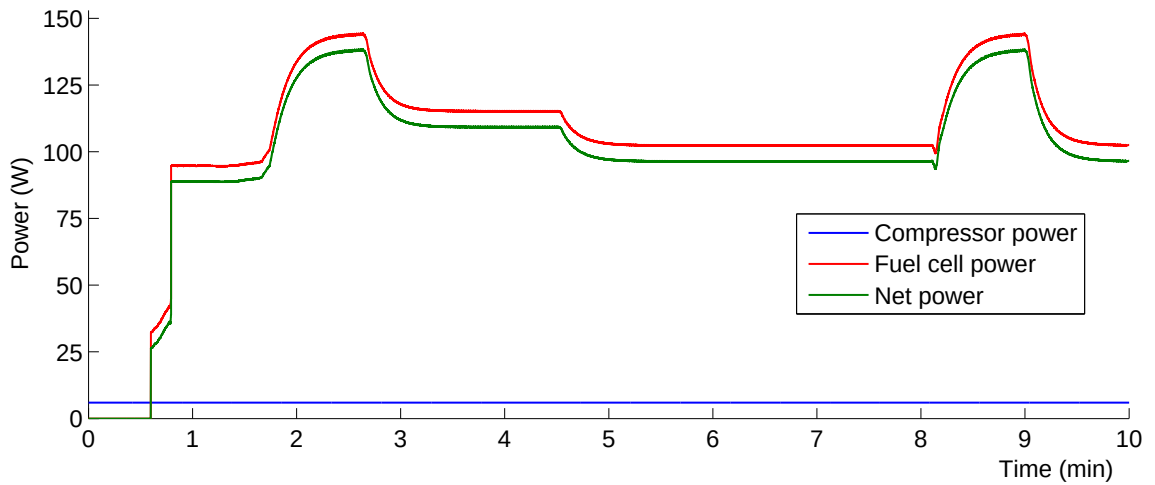


Figure 7.23: Fuel cell system net power output with the constant compressor power

adaptation which minimizes the cell voltage losses, the fuel cell system net power output was maximized. The change of the compressor power as a function of the fuel cell current was properly controlled by the ANFIS controller preventing any sudden changes of compressor power.

The simulation results verified the ANFIS based controller as a combined control architecture in terms of tracking and plant regulating. The research findings have confirmed that the ANFIS based controller offers a novel and comprehensive approach which optimizes the fuel cell system compressor performance. It has resulted in obtaining the maximum net power output from the fuel cell system.

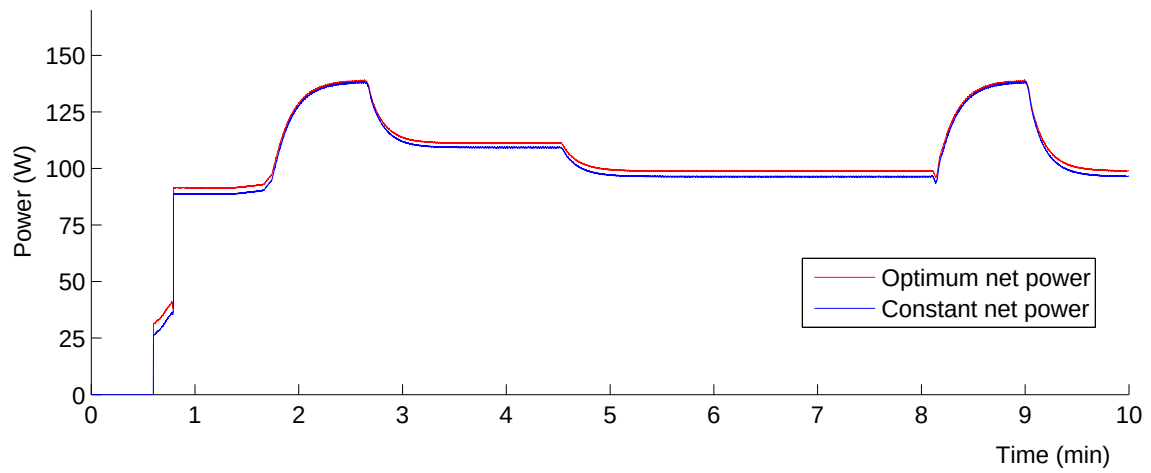


Figure 7.24: Fuel cell net power output comparison between the constant and the optimum configurations

7. FUEL CELL CONTROL AND POWER MANAGEMENT

Power Converters Design and Control

The power electronic interface which consists of a unidirectional and a bidirectional power converters is developed in order to implement the power management architecture described in the chapter (6). The power converters are integrated into a common platform to share the load power between the multiple power sources. The controllability of the power flow is the main advantage of the active hybrid power sharing through a power electronic interface over the passive configuration. In early stages, the linear power regulators were used to step down or step up the voltage output of the power sources. These regulators showed high quality voltage output with minimum ripple current [75]. However, the linear regulator's operational efficiency was considerably low. Later, the switch mode regulators are invented and as a result of that the power converters applications were changed from low power to high power applications. The switch mode power converter shows higher efficiency due to their high switching frequency [75]. Most commonly, the non-isolated switch mode power converters are used in the hybrid power systems due to the several advantages. As the main advantages of the switch mode power converters, the dynamic characteristics of the power converter is improved by the high frequency power electronic switching devices such as IGBTs

8. POWER CONVERTERS DESIGN AND CONTROL

and MOSFETs. In addition to that, high frequency switching minimizes capacitors and inductors capacities requirements hence reduces the sizes of the devices [75]. The non-isolated power converter topology is selected for this project due to its simplicity of the structure and the controllability.

In this chapter, the power converters components such as high voltage side and low voltage side capacitors, inductors sizes are determined based on the load, the battery and the PEM fuel cell system specifications. The theory of operation and the designing stages of the PWM converters are discussed.

8.1 DC Bus Voltage Regulation

The DC bus voltage regulation is a control process that makes a common platform for the both power sources to perform synchronically according to the propulsion power demand. The unidirectional converter operates in the voltage control mode or the current control mode depending on the hybrid system operating states such as the High power state and Charging state. The bidirectional power converter also operates in the voltage control mode and the current control mode similar to the UDC. In addition, the BDC is considered as the main control device of the hybrid system current flow. The BDC decides the amount of the load current shared with the UDC by changing the voltage and current outputs. The load current is distributed between the PEM fuel cell system and the Li-Ion battery by varying the BDC and the UDC PWM signal duty ratios.

Figure (8.1) shows the proposed DC bus regulation process. When the DC bus current is lower than the propulsion system rated value which is 24V at 5.3A, the UDC is operated in the voltage control mode and the BDC is operated in the current control mode. If the DC bus current is higher than the rated value, the UDC is operated in the current control mode and the BDC is switched to the voltage control mode. The voltage and the current compensators generate the errors between the referenced values of the DC bus voltage or current and the actual values. Based on the current or the voltage error, the PWM signal duty ratio is varied.

In the voltage control mode of the UDC, the high voltage (HV) side referenced value is fixed at 24V. For the design considerations, the UDC input voltage range is varied

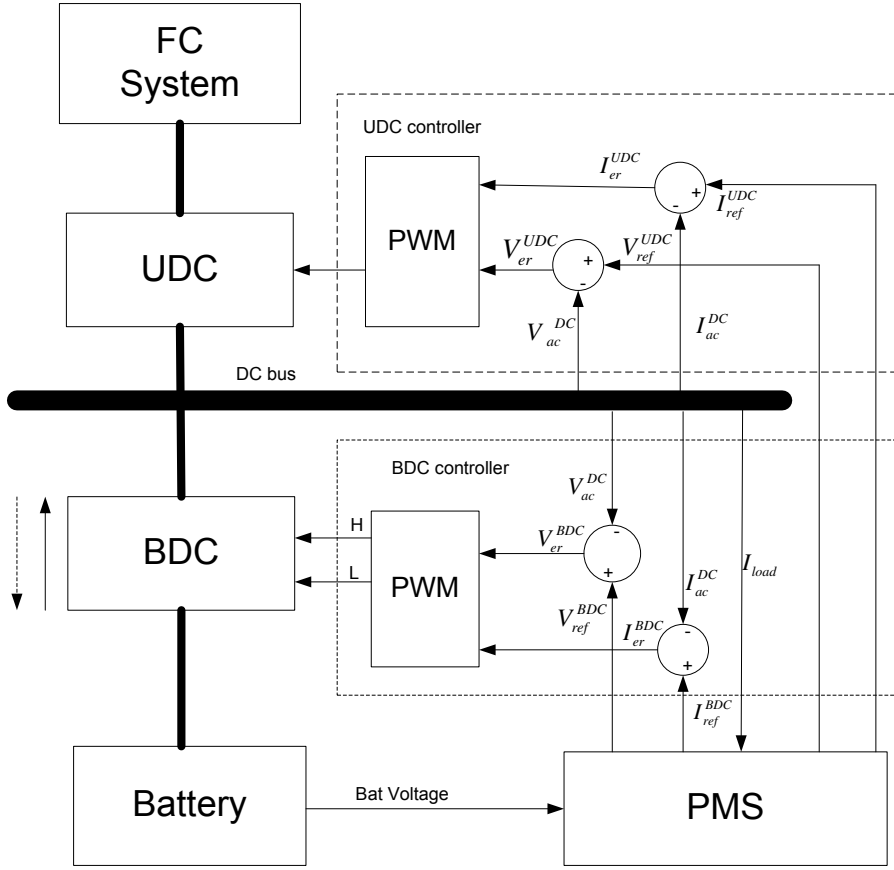


Figure 8.1: DC bus regulation process

between 9V to 22V and the HV side maximum current is limited 5.2A.

During the boost mode of the BDC, the battery operates as the supplementary power source and hence the voltage output is step-up based on the power management system decision. The power management system generates the variable BDC HV side referenced voltage value which is V_{ref}^{BDC} according to the load current sharing requirements. In the boost mode, the HV side is varied between 16V to 30V. When the BDC output voltage is higher than the 24V which is UDC fixed output voltage, the fuel cell system current is gradually reached to zero as the results of the increase in the BDC PWM duty cycle. The load current is equally shared between the fuel cell system and the battery when the BDC HV side is equal to 24V. If the BDC HV side is lower than the 24V, the BDC current is lowered and the current drawn by the UDC is increased. During the buck mode operation of the BDC, the battery is charged by regulating the

8. POWER CONVERTERS DESIGN AND CONTROL

the BDC LV side output at 13.3V. If the battery is charged by the current control mode of the BDC, the charging current is constant at 1.5A.

8.2 Unidirectional Power Converter Topology

A fast dynamic response to the rapid load current change is an essential requirement in the electric propulsion system. The PWM converter with high frequency switching devices improves the dynamic characteristic of the power conversion. In addition to that higher efficiency can be achieved by using the power electronic semiconducting switches such as MOSFETs, IGBT and GTO. In this research, a microcontroller based PWM module is used to generate the high frequency pulses for the switching devices with the changeable conduction time (T_{ON}). The PWM converters show advantages such as wide range of conversion ratio, higher efficiency, less number of components required and commercial availability of the components [75]. The main drawback of the PWM converter is voltage and current losses across the switching devices [75].

The UDC is a boost converter designed with pulse width modulated controller. The schematic diagram of the PWM DC/DC boost converter is shown in (8.2). V_{FC} is the

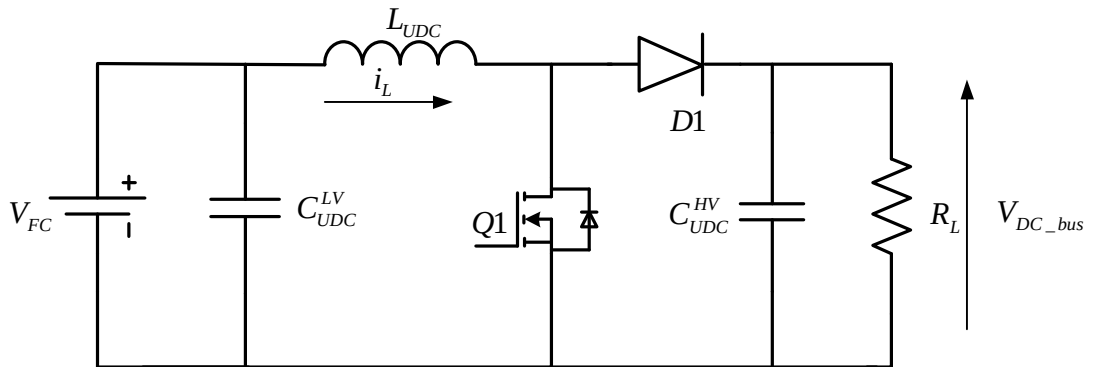


Figure 8.2: Unidirectional converter circuit diagram

fuel cell voltage and the L_{UDC} represents the inductance. The capacitances of the low side capacitor is C_{UDC}^{LV} and the high side capacitor is C_{UDC}^{HV} . $Q1$ is the MOSFET switching device and R_L is the load resistor. The UDC power is flowed from the fuel cell system to the DC bus and the diode $D1$ prevents the reverse current flow from the DC bus to the fuel cell system.

8.2.1 UDC Theory of Operation

The continuous conduction mode (CCM) operation of the unidirectional converter is selected as the designing methodology due to flexibility of controller design [76]. In the CCM, inductor current i_L always stays above zero. It has assumed that the rectifiers are ideal and series losses caused by the wires and the components are ignored. Figure (8.3) and (8.4) show the current flow direction of the UDC during the $Q1$ on state and $Q1$ off state.

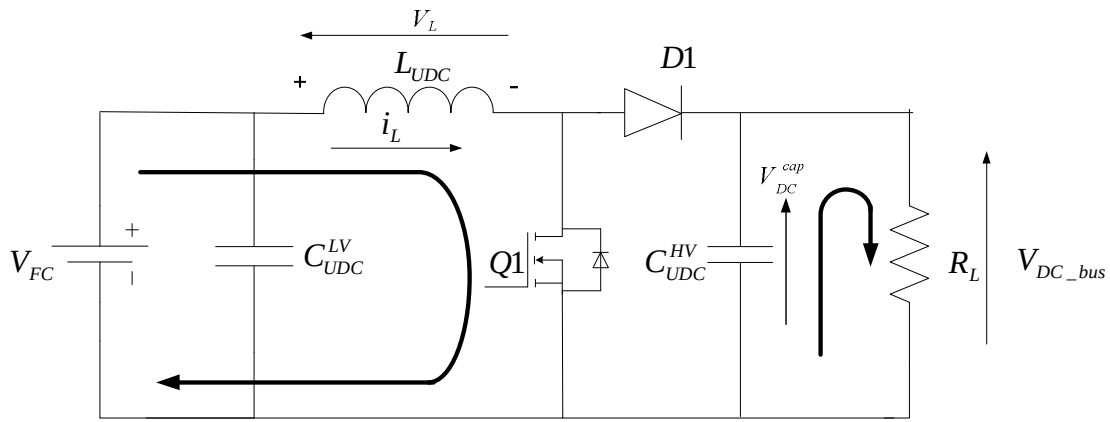


Figure 8.3: UDC current flow during the $Q1$ switch ON state

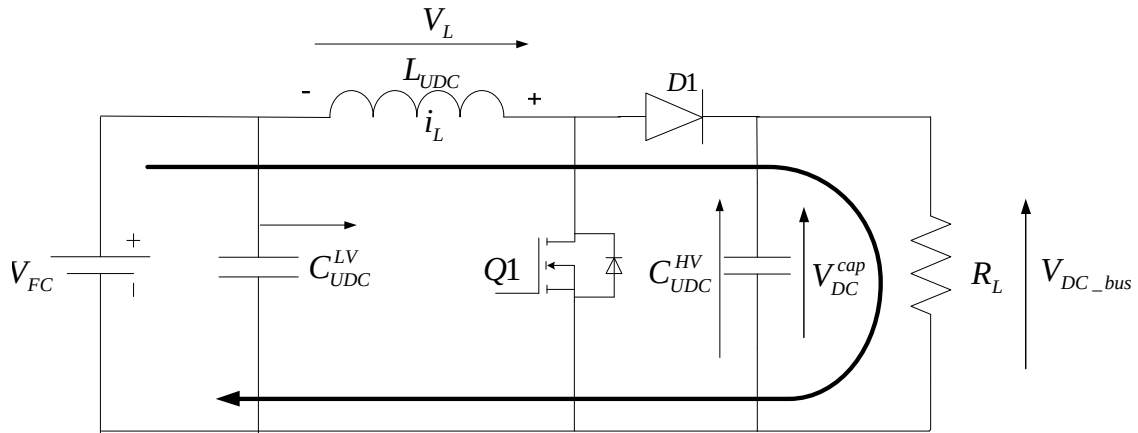


Figure 8.4: UDC current flow during the $Q1$ switch OFF state

When the $Q1$ is switch ON, the inductor current is increased linearly while the DC bus capacitor C_{UDC}^{HV} releases energy. When the $Q1$ is switch OFF, the current flow through the diode $D1$ and releases the energy stored in the inductor. During the switch ON

8. POWER CONVERTERS DESIGN AND CONTROL

mode, the inductor voltage V_L is shown in (8.1) [75],

$$V_L(t) = L \frac{di_L(t)}{dt_{ON}} \quad (8.1)$$

L is the inductance. The duty ratio of the PWM signal is defined as shown in (8.2).

$$D_t = \frac{T_{ON}}{T} \quad (8.2)$$

T is the PWM period with frequency $f = \frac{1}{T}$. From (8.1) and (8.2), the V_L is shown in (8.3).

$$V_L = L \frac{\Delta i_L}{D_t} \cdot f \quad (8.3)$$

By applying the Kirchhoff's voltage law (KVL) to the figure (8.3),

$$-V_{DC}^{cap} + V_{DC_{bus}} = 0 \quad (8.4)$$

$$-V_{FC} + V_L = 0 \quad (8.5)$$

By substituting the (8.3) to the (8.5), the relationship between the V_{FC} and L can be obtained as shown in (8.6).

$$-V_{FC} + L \frac{\Delta i}{D_t} \cdot f = 0 \quad (8.6)$$

During the T_{ON} , the $D1$ switch is *off* mode and the $V_{DC_{bus}} = V_{DC}^{cap}$.

When the $Q1$ is switched OFF, the energy accumulated in the inductor releases through the load R and the capacitor C_{UDC}^{HV} . By applying the KVL to the figure (8.4),

$$-V_{FC} - V_L + V_{DC_{bus}} = 0 \quad (8.7)$$

During the T_{off} period, the V_L is defined as in (8.8)

$$V_L(t) = L \frac{di_L(t)}{dt_{off}} \quad (8.8)$$

$$V_{L_{off}} = L \frac{\Delta i_L}{(1 - D_t)} \cdot f \quad (8.9)$$

By substituting the $V_{L_{off}}$ into the (8.7),

$$V_{DC_{bus}} - V_{FC} = L \frac{\Delta i_L}{(1 - D_t)} \cdot f \quad (8.10)$$

From (8.7) and (8.10), the input and output voltage ratio is defined as shown in (8.11)

$$\begin{aligned} (V_{DC_{bus}} - V_{FC})(1 - D_t) &= D_t \cdot V_{FC} \\ V_{DC_{bus}} &= \frac{V_{FC}}{(1 - D_t)} \end{aligned} \quad (8.11)$$

8.2.2 Unidirectional Power Converter Design

The PWM controlled UDC which is shown in figure (8.2) is designed as a part of the implementation framework of the hybrid system. The design specifications for the UDC are shown in table (8.1). The capacitive and inductive components are developed to meet the maximum power requirements.

Table 8.1: *UDC specifications*

Maximum Power	150W
Maximum input voltage	18V
Minimum output voltage	13V
Regulated voltage output	24V
Switching frequency	20kHz
Percentage of current ripple	1%

8. POWER CONVERTERS DESIGN AND CONTROL

The PEM fuel cell system voltage output is ranged between the 13V and 18V. At the minimum voltage of the fuel cell system which is $V_{FC_{min}} = 13V$, the power converter operates in the maximum conduction time to boost the voltage output. From (8.11), the maximum duty ratio D_{max} is obtained as shown in (8.12).

$$D_{t_{max}} = 1 - \frac{V_{FC_{min}}}{V_{DC_{bus}}} \quad (8.12)$$

$$D_{t_{max}} = 0.46 \quad (8.13)$$

When the fuel cell system voltage output is maximum ($V_{FC_{max}} = 18V$), the minimum conduction time is applied by minimizing the PWM duty ratio. Equation (8.14) shows the minimum duty ratio D_{min} for the UDC.

$$D_{t_{min}} = 1 - \frac{V_{FC_{max}}}{V_{DC_{bus}}} \quad (8.14)$$

$$D_{t_{min}} = 0.25 \quad (8.15)$$

Therefore, the range of the UDC duty ratio is obtained as $0.25 \leq D_{t_{Q1}} \leq 0.46$.

8.2.2.1 Inductor Design

The inductor design specifications are calculated based on the minimum and maximum conduction times of the converter. The UDC switching frequency is $20kHz$ and a PWM signal with a constant switching period $50\mu s$ is supplied to the MOSFET switching device $Q1$. For the each minimum and maximum conduction mode, the inductance of the converter is determined and the highest value is selected for the design purposes.

When the UDC operates in $D_{t_{max}}$, the converter conduction time T_{ON} is shown in (8.16),

$$T_{ON}^{max} = D_{t_{max}} \frac{1}{f} \quad (8.16)$$

$$T_{ON}^{max} = 23\mu s \quad (8.17)$$

In the CCM operation, the AC ripple current is imposed over the load current due to the switch *on* and *off* states of the $Q1$ switching device. It has assumed that the ripple

current is 1% of the mean current $I_{mean} = 6.25A$. The peak to peak variation of the inductor current ΔI_L is shown in (8.18).

$$\Delta I_L = 2(0.01)I_{mean} \quad (8.18)$$

$$\Delta I_L = 0.125 \quad (8.19)$$

From the (8.3) the inductance of the power converter is derived as shown in (8.20)

$$L_{UDC} = \frac{V_{FCmin} \Delta t_{ON}^{max}}{\Delta I_L} \quad (8.20)$$

$$L_{UDC} = 2.4mH \quad (8.21)$$

When the UDC operates in D_{min} , (8.22) shows the minimum conduction time T_{ON}^{min} .

$$T_{ON}^{min} = D_{tmin} \frac{1}{f} \quad (8.22)$$

$$T_{ON}^{min} = 12.5\mu s \quad (8.23)$$

The inductance required during the V_{FCmax} is shown in (8.24).

$$L_{UDC} = \frac{V_{FCmax} \Delta t_{ON}^{min}}{\Delta I_L} \quad (8.24)$$

$$L_{UDC} = 1.8mH \quad (8.25)$$

Equation (8.20) shows that the minimum inductance value required for the UDC should be greater than $2.4mH$. At the minimum fuel cell voltage, the higher inductance value is required for the maximum ripple amplitude. The higher inductance value increases the limit for maximum ripple amplitude. However, the high inductance value shows drawbacks such as slow transient response, increase in the inductor mass and higher internal resistance of the inductor. The inductance $L_{UDC} = 2.5mH$ is selected for the UDC designing process of this project.

A Ferrite core which has high magnetic permeability with low electrical conductivity is selected as the inductor core. The core factor of the selected Ferrite core is $\sum \frac{l}{A} =$

8. POWER CONVERTERS DESIGN AND CONTROL

$0.454mm^{-1}$ and relative permeability is μ_r is 1950 [77]. The Ferrite core permeability is derived as shown in (8.26).

$$\mu_c = \mu_r \times \mu_0 \quad (8.26)$$

$$\mu_c = 1950 \times 1.257 \times 10^{-6}$$

$$\mu_c = 2.45 \times 10^{-3} Hm^{-1}$$

The reluctance of the ferrite core is proportional to the core factor and inversely proportional to the permeability [78].

$$R_c = \frac{\sum(\frac{l}{A})}{\mu_c} \quad (8.27)$$

$$R_c = 1.85 \times 10^5 H^{-1}$$

The inductance factor A_l is,

$$A_l = \frac{10^9}{R_m} \quad (8.28)$$

$$A_l = 5400nH/turn^2$$

Equation (8.29) shows the relationship between the inductance and the number of turns N_t [78]. For the UDC inductor, 21 turns are required to obtain $2.5mH$.

$$L_{UDC} = A_l \times N_t^2 \quad (8.29)$$

$$N_t = \sqrt{\frac{2.56mH}{5400nH/turn^2}}$$

$$N_t = 21 \quad (8.30)$$

At the maximum power of the inductor $P_{max} = 150W$, the inductor maximum current

is $6.25A$.

$$\begin{aligned} I_{L_{max}} &= \frac{P_{max}}{V_{dc_{bus}}} \\ I_{L_{max}} &= 6.25A \end{aligned} \quad (8.31)$$

The selected copper wire for the inductor is sufficient to transfer maximum $15A$ current.

8.2.2.2 DC Bus Capacitance

In the CCM operation, the DC bus capacitor ($C_{DC_{bus}}$) acquires the energy during the $Q1$ is *OFF* mode and releases the energy when the $Q1$ is *ON* state. The $C_{DC_{bus}}$ capacitance should be sufficient to provide the energy during the propulsion system maximum power which is $6.25A$ for $23\mu s$ maximum conduction time. The high frequency ripple current caused by the inductor generates the voltage ripple across the DC bus terminal. The capacitance required for limit the ripple voltage amplitude δV in boost converter is derived in (8.32) [76]. The capacitor net charge δQ is,

$$\begin{aligned} \delta Q &= C_{dc}\delta V \\ \delta Q &= i_c\delta t \\ C_{dc} &= \frac{i_c\delta t}{\delta V} \end{aligned} \quad (8.32)$$

C_{dc} is the capacitance and the i_c is the capacitor current. δt represents the $Q1$ conduction time T_{ON} . Assume that the voltage variation from the nominal point which is $24V$ is 2% and hence the ripple voltage amplitude is $\delta V = 0.48V$. From the (8.32), the minimum DC bus capacitance $C_{DC_{min}}$ can be expressed,

$$C_{DC_{min}} = \frac{6.25A \times 23 \times 10^{-3}s}{0.48V} \quad (8.33)$$

$$C_{DC_{min}} = 299\mu F \quad (8.34)$$

In order to supply the continuous power through the DC bus by minimizing the effects of the ripple current, $299\mu F$ capacitance is required for the DC bus capacitor.

8.3 Bidirectional Converter Topology

The bidirectional converter changes the current flow direction of the battery according to the load power requirement. The BDC boosts up the battery voltage during the high power state and the start-up state. The BDC buck mode is activated for the battery charging state. The non-isolated PWM controlled power converter is selected for the BDC designing process. The BDC circuit diagram is shown in figure (8.5). V_{BAT} is the battery voltage and the C_{BDC}^{LV} is the LV side capacitor. L_{BDC} is denoted by the BDC inductor and $Q2$ and $Q3$ are MOSFET switches. The capacity of the DC_{bus} capacitor bank is denoted by the C_{BDC}^{HV} .

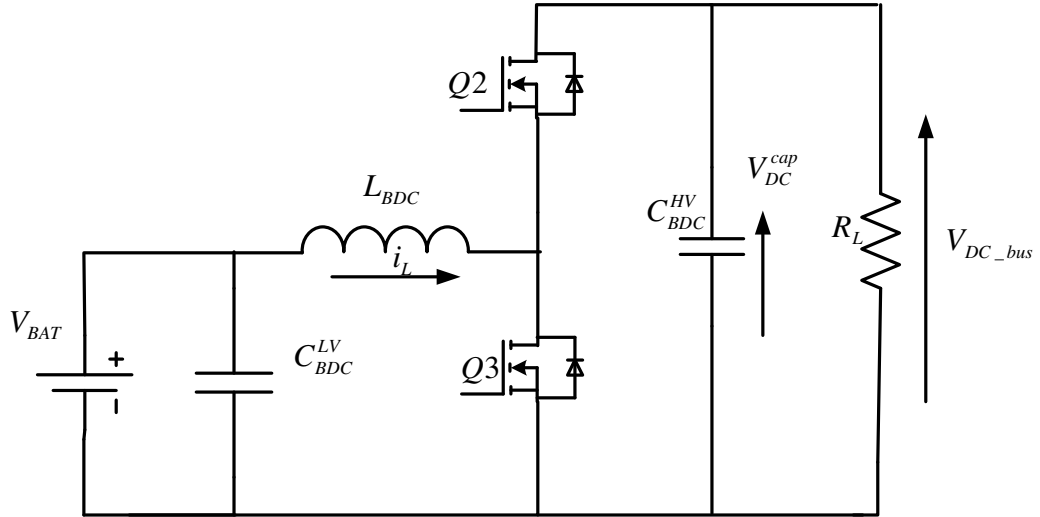


Figure 8.5: Bidirectional converter circuit diagram

When the energy flows from the LV to the HV side during the boost mode, $Q3$ operates as the active switch and the $Q2$ is the passive switch. The BDC current flow diagram during the boost mode is shown in figure (8.6). The BDC boost mode operation is similar to the UDC boost mode operation. The $Q2$ switch is operated as a diode.

Figure (8.7) shows the power flow during the buck operation. The $Q2$ switch is the active switch in the buck mode operation and the $Q3$ in the passive state. When the $Q2$ is *ON* state, the current flow from the HV side to the LV side and the energy is accumulated in the inductor. Figure (8.8) shows the power flow during the $Q2$ is *OFF* mode.

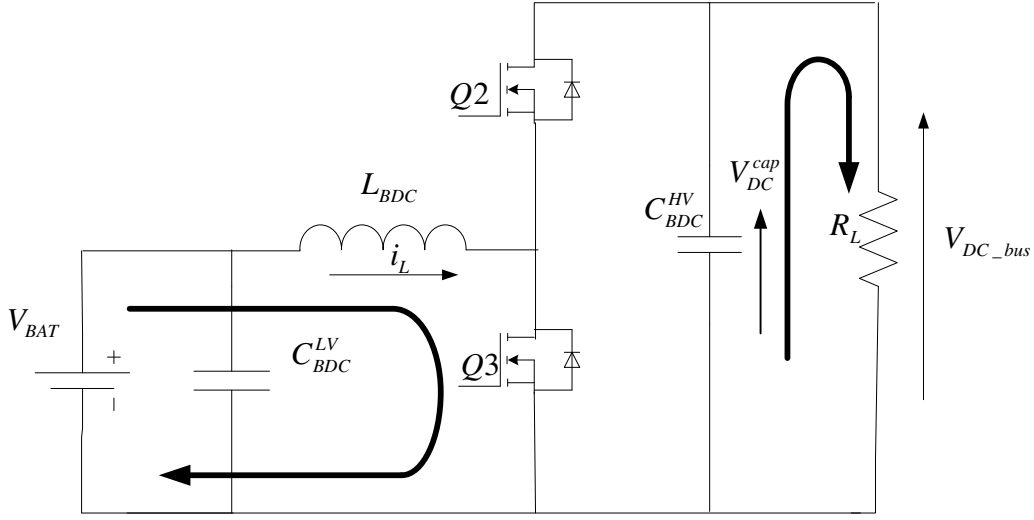


Figure 8.6: BDC current flow during the boost mode

8.3.1 BDC Theory of Operation

The BDC switches the MOSFET devices within the conduction current mode (CCM) and prevents the zero current flow in the inductor. The relationship between the HV side voltage and the LV side in the buck mode operation is derived in (8.39). By applying the KVL to the figure(8.7),

$$-V_{DC_{bus}} + V_L + V_{BAT} = 0 \quad (8.35)$$

$$-V_{DC_{bus}} + L_{BDC} \frac{\Delta i_L}{D_t} \cdot f + V_{BAT} = 0 \quad (8.36)$$

When the Q2 is switch off, apply KVL for figure (8.8),

$$-V_L + V_{BAT} = 0 \quad (8.37)$$

$$V_{BAT} = L_{BDC} \frac{\Delta i_L}{1 - D_t} \cdot f \quad (8.38)$$

From (8.36) and (8.38), the BDC LV side voltage can be obtained as shown in (8.39).

$$V_{BAT} = D_t \cdot V_{DC_{bus}} \quad (8.39)$$

8. POWER CONVERTERS DESIGN AND CONTROL

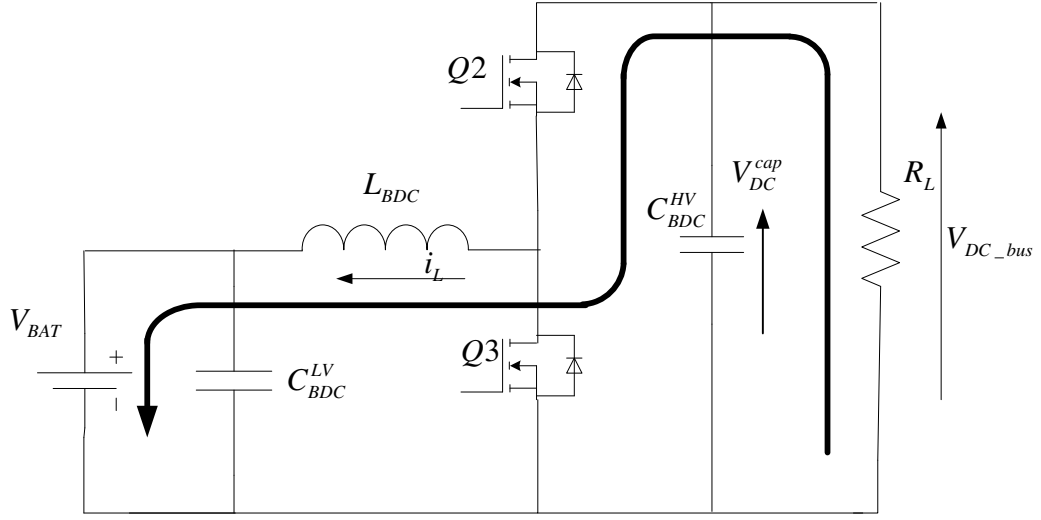


Figure 8.7: BDC during the Q2 ON state

8.3.2 Bidirectional Converter Design

The bidirectional converter shown in figure (8.5) consists of an inductor, two MOSFET switches, a LV side capacitor and the DC bus capacitor. In order to determine the BDC specifications, the converter characteristics of the boost mode and the buck mode are analyzed. The BDC required specifications are shown in table (8.2)

8.3.2.1 BDC Boost Mode Operation

The boost mode of the BDC operates similar to the UDC boost mode and only difference is the switch $Q2$ is maintained at the passive state. The Li-Ion battery minimum voltage is 10V and the maximum value is 12.2V. The BDC HV side output is varied between the 16V to 30V. The conduction times in each voltage mode are determined and the maximum conduction time is used for selecting the DC bus capacitance. When the battery voltage is maximum 12.2 and the HV output is 30V, the duty ratio of the $Q2$ PWM signal is shown in (8.40).

$$D_t = 1 - \frac{V_{bat}^{max}}{V_{DC_{bus}}^{max}} \quad (8.40)$$

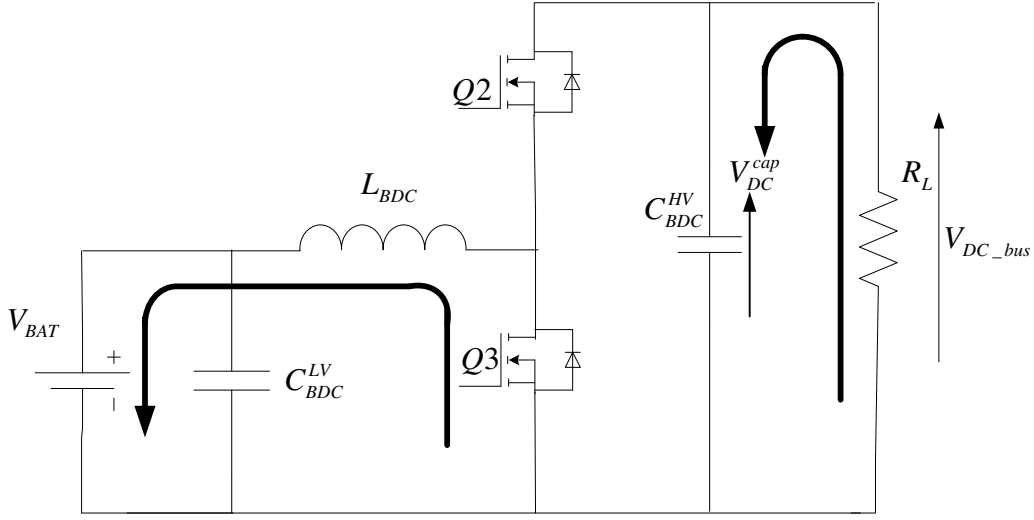


Figure 8.8: BDC during the Q2 OFF state

$$D_t = 1 - \frac{12.2V}{30V}$$

$$D_t = 0.6$$

From (8.2) the current conduction time is determined $T_{ON} = 30\mu s$. If the battery voltage is minimum and the HV side is 30V, the Q2 duty ratio is shown in (8.41).

$$D_t = 1 - \frac{V_{bat}^{min}}{V_{DC_{bus}}^{max}} \quad (8.41)$$

$$D_t = 1 - \frac{10V}{30V}$$

$$D_t = 0.67$$

The T_{ON} time during the battery minimum voltage is $33.5\mu s$. During the HV side minimum output 16V, the conduction times of the Q2 at minimum and maximum voltages are shown in (8.42) and (8.43).

$$D_t = 1 - \frac{V_{bat}^{max}}{V_{DC_{bus}}^{min}} \quad (8.42)$$

$$D_t = 1 - \frac{12.2V}{16V}$$

8. POWER CONVERTERS DESIGN AND CONTROL

Table 8.2: BDC specifications

Boost mode	LV side minimum input voltage	10V
	LV side maximum input voltage	12.2V
	HV side minimum output voltage	16V
	HV side maximum output voltage	30V
Buck mode	LV side output voltage	13.3 V
	HV side input voltage	24 V
Switching frequency		20kHz

$$D_t = 0.24$$

$$D_t = 1 - \frac{V_{bat}^{min}}{V_{DC_{bus}}^{min}} \quad (8.43)$$

$$D_t = 1 - \frac{10V}{16V}$$

$$D_t = 0.38$$

From (8.2), T_{ON} at the maximum battery voltage is $12\mu s$ and at the minimum battery voltage is $19\mu s$. From the above derivations, the maximum conduction time $T_{ON} = 33.5\mu s$ is required at the maximum DC bus voltage and the minimum battery voltage. Therefore, the DC bus capacitor must be sufficient to supply the DC bus power for $33.5\mu s$ duration. For the 2% ripple voltage and the maximum current $6.25A$, the DC bus capacitance is shown in (8.44).

$$C_{DC_{bus}} = \frac{6.25A \times 33.5 \times 10^{-6}s}{30V \times 0.02} \quad (8.44)$$

$$C_{DC_{bus}} = 348\mu F$$

For the BDC boost mode operation, the required minimum inductance is determined similar to the UDC. During the maximum power of the propulsion system, the ripple current Δi_{BDC} percentage is considered as the 1%. By using the (8.1), the minimum inductance required during the boost mode is obtained in (8.45),

$$\begin{aligned}
 L_{BDC} &= \frac{V_{BAT}^{min} t_{ON}^{max}}{\Delta I_L} \\
 L_{BDC} &= \frac{10V \times 33.5 \times 10^{-6}}{2 \times 0.01 \times 6.25} \\
 L_{BDC} &= 2.68mH
 \end{aligned} \tag{8.45}$$

8.3.2.2 BDC Buck Mode Operation

The bidirectional converter buck mode is activated for the battery charging process. The MOSFET $Q3$ is the active switch and the $Q2$ remains in the passive state. The battery charging voltage is constant at $13.3V$ and the HV side input is $24V$. The BDC LV side voltage output is regulated at $13.3V$. When the battery is at minimum voltage $V_{bat} = 10V$, the duty ratio of the $Q3$ PWM signal is derived in (8.46) by substituting the voltages into (8.39).

$$\begin{aligned}
 D_t &= \frac{10}{24} \\
 D_t &= 0.41
 \end{aligned} \tag{8.46}$$

At the maximum battery voltage which is $12.2V$, the required maximum duty ratio is shown in (8.47).

$$\begin{aligned}
 D_t &= \frac{12.2}{24} \\
 D_t &= 0.51
 \end{aligned} \tag{8.47}$$

8. POWER CONVERTERS DESIGN AND CONTROL

8.3.2.3 Inductance

The required BDC inductance L_{bat} is higher at the minimum battery voltage. The ripple current Δi of the battery maximum charging current 2.1A is 1%. The minimum inductance required for the BDC is obtained in (8.48) ,

$$\begin{aligned}
 L_{BDC} &= \frac{V_{LV}(1 - D_{t_{T1}})}{\Delta i_{bat} \cdot f} \\
 L_{BDC} &= 10 \times \frac{10V(1 - 0.41)}{0.021 \times 20000} \\
 L_{BDC} &= 14mH
 \end{aligned} \tag{8.48}$$

8.3.3 LV Side Capacitance

The BDC LV side capacitor minimizes the ripple voltage across the battery terminal. The constant voltage is important during the charging process. Hence, the capacitance must be able to encounter the voltage drop by the switching process. The figure (8.9) shows the current flow during the buck mode.

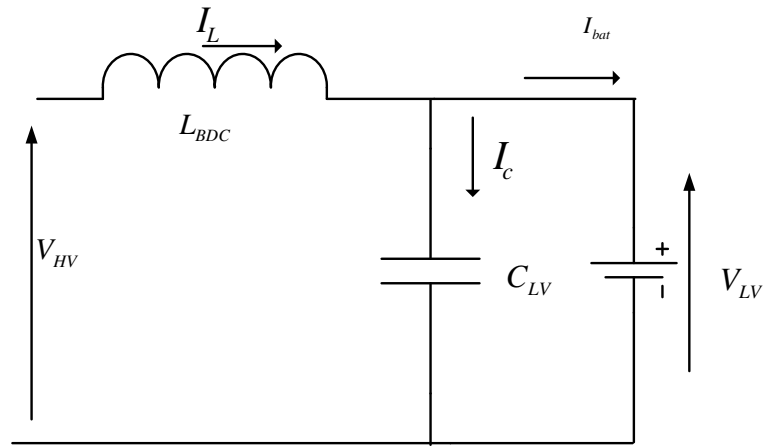


Figure 8.9: BDC current flow during the buck mode

I_{bat} is the average battery charging current and I_c is the capacitor current. In order to obtain the smooth LV side output, the C_{LV} should store and releases the energy during the switching. Figure (8.10) shows the energy stored in the capacitor ΔQ referenced to the battery current I_{bat} .

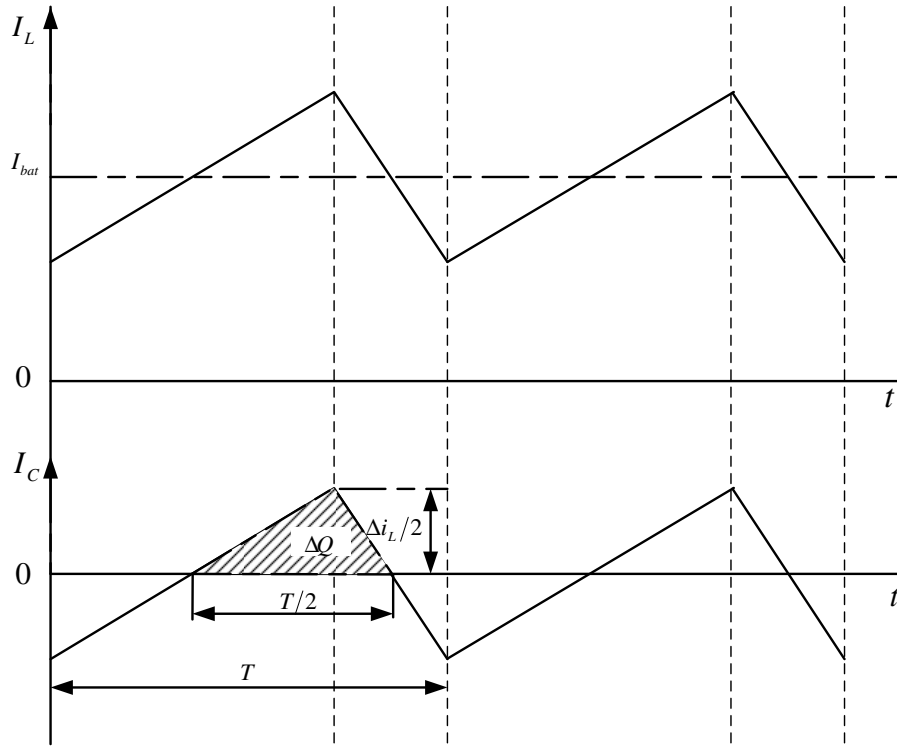


Figure 8.10: LV side capacitor energy variation with time

The ΔQ is expressed as,

$$\Delta Q = \frac{1}{2} \left(\frac{\Delta I_L}{2} \right) \left(\frac{T}{2} \right) \quad (8.49)$$

$$\Delta Q = \frac{\Delta I_L}{8f} \quad (8.50)$$

By assuming the capacitor internal resistance is minimum, From (8.32) and (8.49), the capacitance of the C_{LV} is determined in (8.51). The maximum capacitance is required at the minimum battery voltage and hence the required minimum duty cycle of the $Q2$ is $D = 0.41$. The voltage ripple across the ΔV_{bat} is considered 2%.

$$\begin{aligned} C_{LV} &= \frac{\Delta Q}{\Delta V} \\ C_{LV} &= \frac{V_{bat}(1 - D_{T1})}{8f^2 L_{bdc} \Delta V_{bat}} \\ C_{LV} &= 66 \mu F \end{aligned} \quad (8.51)$$

8. POWER CONVERTERS DESIGN AND CONTROL

Table (8.3) shows the required minimum values for each component. Figure (8.11) illustrates the developed bidirectional converter for the hybrid electric system.

Table 8.3: BDC components specifications

Component	Value
Inductor	$2.68mH$
DC bus capacitor	$348\mu F$
LV side capacitor	$66\mu F$

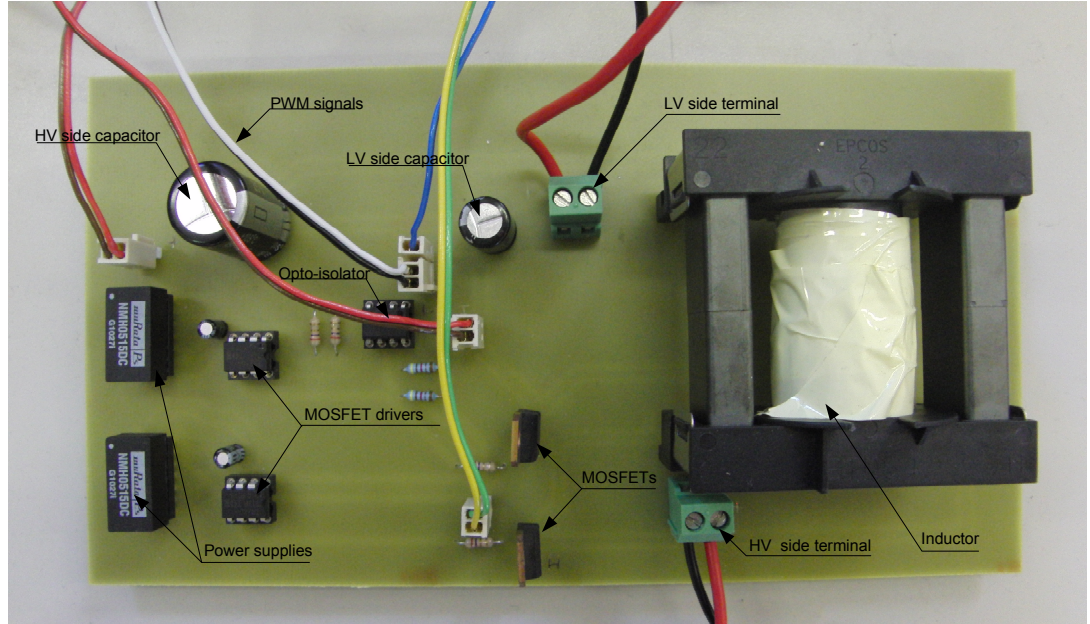


Figure 8.11: Bidirectional converter developed for hardware set-up

8.4 Pulse Width Modulation and Embedded Control

The power converter's PWM signal conduction time period T_{ON} is increased or decreased to maximize or minimize the HV side voltage respectively. The converter desired HV side voltage which is $V_{HV_{ref}}^{DC}$ is compared with the actual DC bus voltage

$V_{DC_{ac}}$ and voltage error (V_{er}) is minimized by increasing or decreasing the conduction time of the relevant MOSFET switch. If the $V_{er} > 0$, the $V_{DC_{ac}}$ is increased by adding Δt time to duty ratio D_t . Figure (8.12) shows the difference between the reference signal conduction time T'_{ON} and the actual signal conduction time T_{ON} at the positive V_{er} .

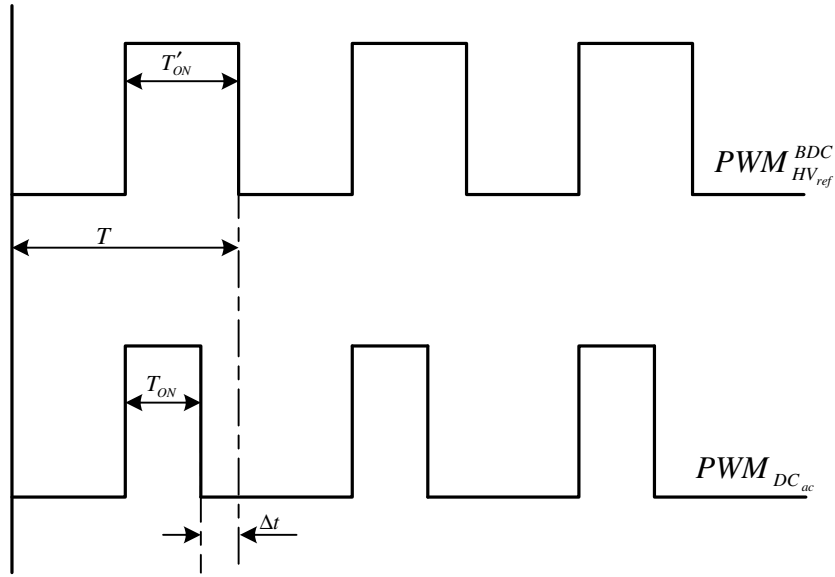


Figure 8.12: Changes in duty ratio

The $V_{HV_{ref}}^{DC}$ which is shown in figure (8.12) has 50% duty cycle and the desired HV side voltage is 24V. The PWM period is $50\mu s$ and the desired conduction time $T'_{ON} = 25\mu s$. The $V_{DC_{ac}}$ conduction time $T_{ON} = 16.66\mu s$ and duty ratio is 33.3%. Equation (8.56) shows the required Δt .

$$\Delta t = T'_{ON} - T_{ON} \quad (8.52)$$

$$\Delta t = 8.3\mu s \quad (8.53)$$

The PWM signal duty ratio updating process during the voltage control mode is shown in figure (8.13).

8. POWER CONVERTERS DESIGN AND CONTROL

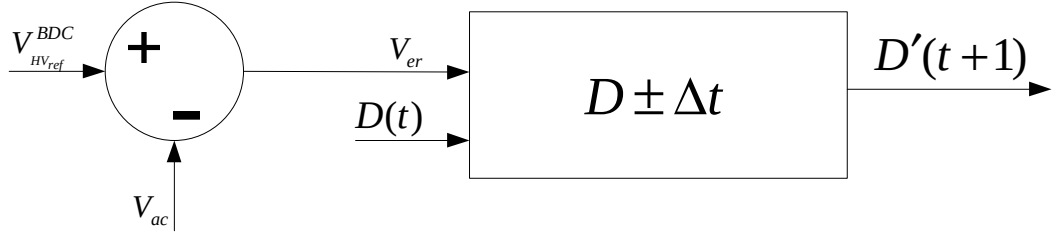


Figure 8.13: PWM signal duty ratio changes at the voltage control mode

8.4.1 Microcontroller PWM Signal Control

The micro-controller PWM module has period register value (PR) to represent the T_{ON} of the PWM signal. The controller timers are configured for 1 : 1 prescaler value and the oscillator frequency $FOSC$ is $8MHz$. Equation (8.56) shows the PR value for 0% duty cycle at $20kHz$ frequency PWM signal.

$$PWM_{period} = (PR + 1) \cdot T_{CY} \cdot (TimerPrescalerValue) \quad (8.54)$$

$$T_{CY} = \frac{2}{FOSC} \quad (8.55)$$

$$PR = 199 \quad (8.56)$$

Therefore, the range of the PR value is defined as $0 \leq PR \leq 199$. The 50% of the duty cycle is represented by the $PR = 99$. By changing the $1PR$ value, the $0.25\mu s$ of the T_{ON} is varied as shown in (8.58).

$$1PR = \frac{50\mu s}{200} \quad (8.57)$$

$$1PR = 0.25\mu s \quad (8.58)$$

From (8.56) and (8.58), the PR value required to boost the voltage is shown in (8.60),

$$\begin{aligned} \Delta PR &= \frac{8.3\mu s}{0.25\mu s} \\ \Delta PR &= 33 \end{aligned} \quad (8.59)$$

The $V_{DC_{ac}}$ at $T_{ON} = 16.66\mu s$ is shown in (8.61),

$$V_{DC_{ac}} = \frac{16.67\mu s}{25\mu s} \times 24V \quad (8.60)$$

$$V_{DC_{ac}} = 16V \quad (8.61)$$

By adding 33 to the period register value PR , the actual DC bus value is reached to the desired value $24V$.

$$V_{DC_{ac}} = V_{HV_{ref}}^{BDC} \quad (8.62)$$

The voltage gain ΔV per each $1\mu s$ is shown in (8.64),

$$\Delta V = \frac{V_{er}}{\Delta t} \quad (8.63)$$

$$\Delta V = 0.96V\mu s^{-1} \quad (8.64)$$

The controller changes the PR value continuously in order to reached desired voltage from the existing voltage.

8. POWER CONVERTERS DESIGN AND CONTROL

Experiments, Results and Discussions

The power management architecture which is described in chapter (6) is validated by developing the hardware set-up for real time operation. The hybrid electric propulsion system was emulated in different test conditions and results were compared with the simulation results. The main objective of the hardware development was to verify the proposed power management system performances. The experimentations were mainly focused to identify the power management system performances in the real time environment.

9.1 The Hybrid Electric Experimental Setup

The hybrid electric experimental set-up was mainly consisted with a power controller, a primary power source, a secondary power source, a unidirectional power converter, a bidirectional power converter, a PMBL DC propulsion motor and a motor controller. The main power control board was developed with a Microchip microcontroller and a sensor interface which consisted of current sensors and voltage dividers. Figure (9.1) shows the experimental setup developed for this project. The components specifica-

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

tions were the same as the simulations models. A Li-Ion battery was used as the secondary power source. The PMDC brushless motor generated the load current signal.

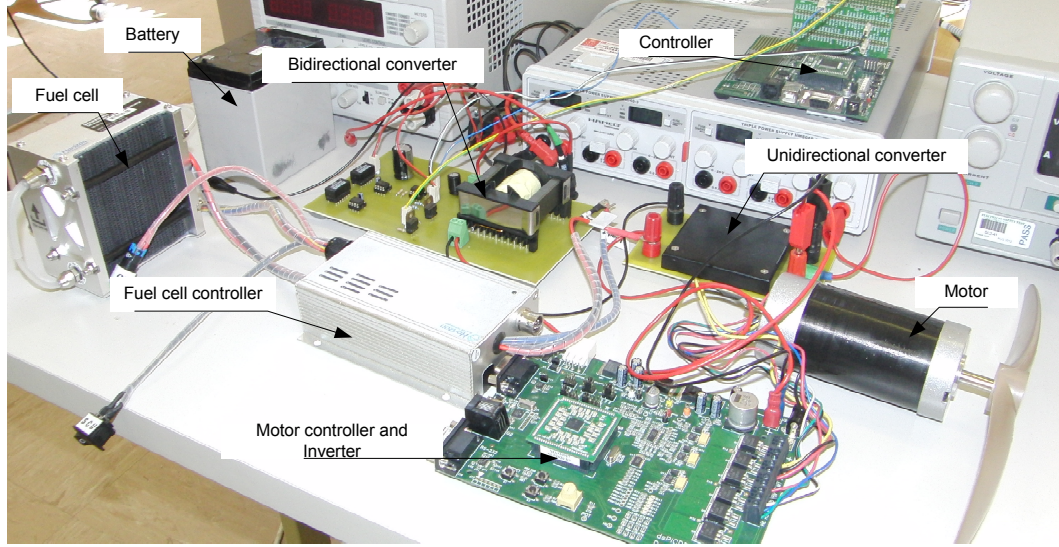


Figure 9.1: *Hardware set-up developed for experimentation*

A programmable power source was used as a primary power source instead of the PEM fuel cell system due to the practical difficulties such as health and safety issues on hydrogen gas installation. The voltage output of the primary power source was programmed similar to the polarization curve of the PEM fuel cell as shown in figure (9.2). The power supply operated in unregulated mode and changed the operating power with the load current.

9.2 Experiment (1): Start-Up State Test

The experiment (1) was conducted to identify the power management system characteristics during the hybrid system Start-up state. The Start-up state was configured to power the fuel cell system balance of plant load by using the battery and later the load current was swapped into the fuel cell from the battery. Even though the fuel cell system was not operational during the experiment, the fuel cell air supplying blower was connected to the DC bus as the fuel cell auxiliary load. The load current distribu-

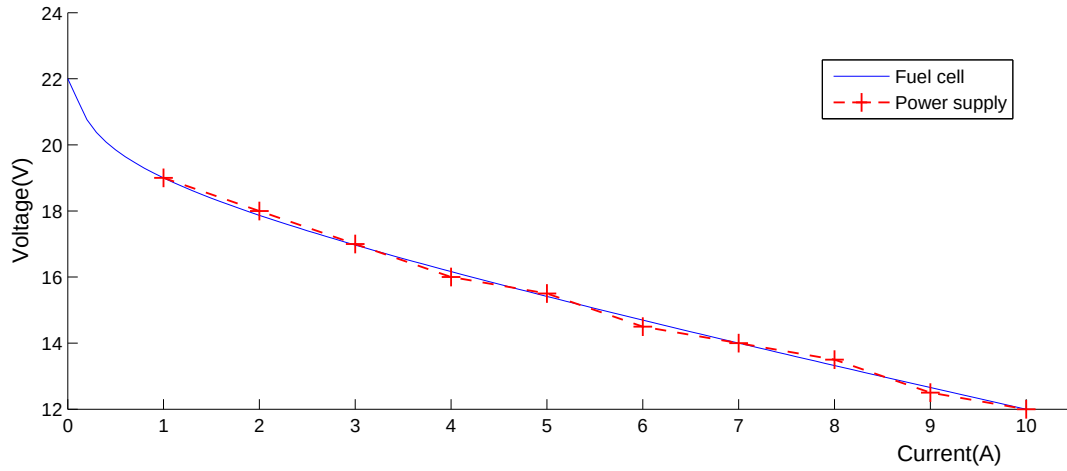


Figure 9.2: Polarization curves comparison between the fuel cell and the programmable power supply

tion during the Start-up state was measured and the terminal voltage variations of the battery and the primary power source also measured.

9.2.1 Procedure

Following initial conditions were required for the Start-up process:

1. The BDC was switched to the boost mode operation.
2. The UDC was switched off mode.
3. The Li-Ion battery terminal voltage was $> 12V$.

The Start-up state which is described in the Chapter 6.2.1 was emulated by loading the propulsion motor current. The DC load current was gradually increased up to $2.8A$ at the $24V$ DC bus voltage. The Start-up state was limited to 155 seconds time period. During the Start-up state, the BDC was operated in the current control mode and the UDC was operated in the voltage control mode.

9.2.2 Results

The Start-up state power sharing process showed that the current and voltage variations of the power sources were according to the proposed algorithm. Figures (9.3) and

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

(9.4) show the battery current and the voltage variations during the Start-up process. The experiment data was taken for 450 seconds time period. The battery current was maximized up to $6.5A$ and after the fuel cell settling time, the battery current was reduced gradually. The fuel cell settling time finished at 80 seconds. Figure (9.5) shows the DC bus voltage changes during the Start-up process. When the BDC was operated in the boost mode, the DC bus voltage was maximized to $27.5V$. Figure (9.6) shows the UDC LV side current which was the primary power source current variation during the Start-up state. The UDC LV side voltage variation is shown in figure (9.7). When the load power was swapped into the UDC after 155 seconds, the primary power source voltage was decreased to minimum $15.15V$.

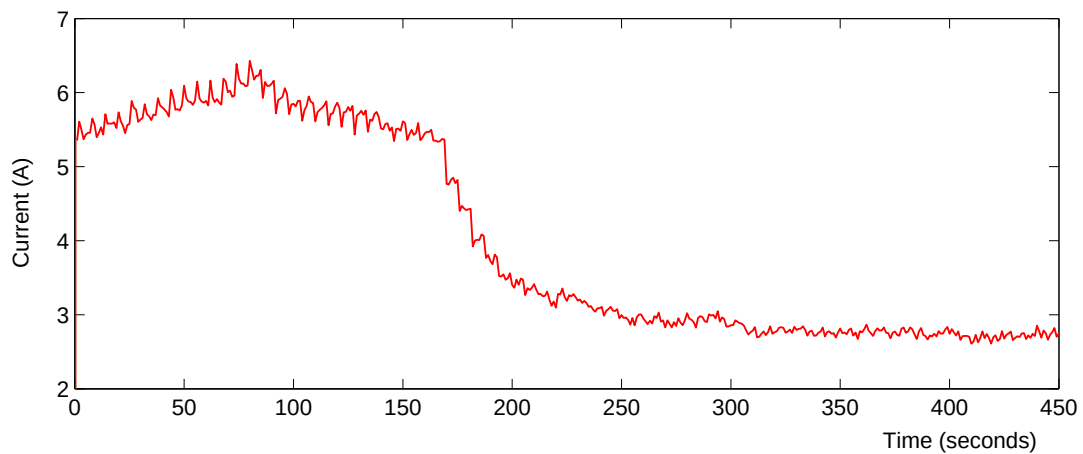


Figure 9.3: *Battery current variations during the Start-up state*

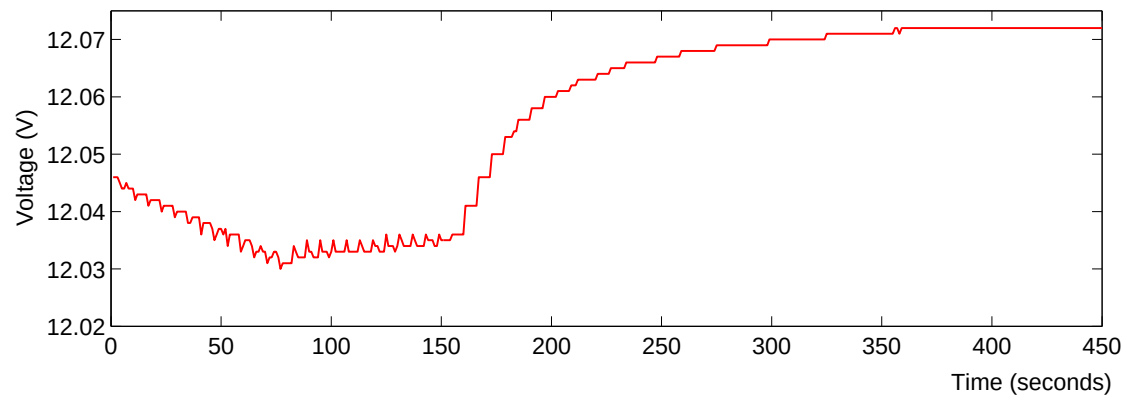


Figure 9.4: *Battery voltage variations during the Start-up state*

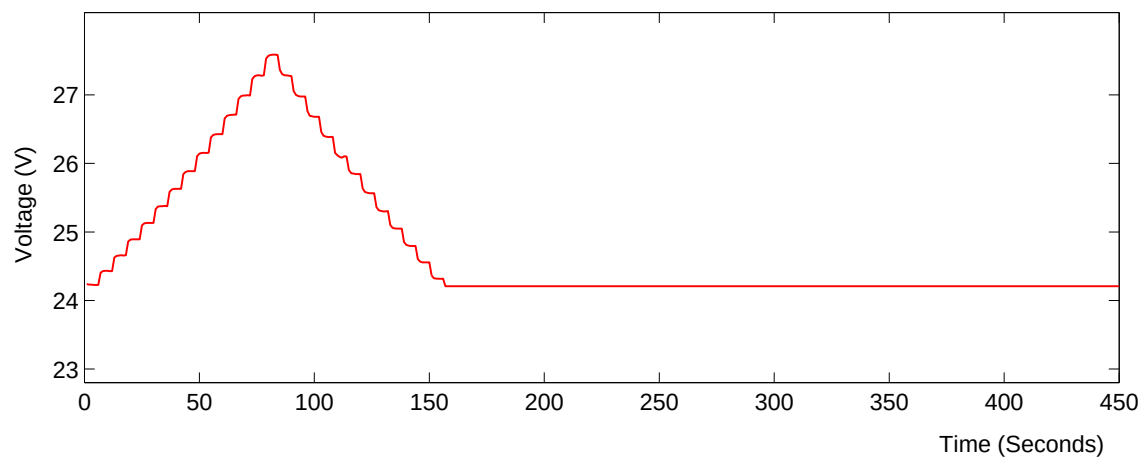


Figure 9.5: *DC bus voltage variations during the Start-up state*

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

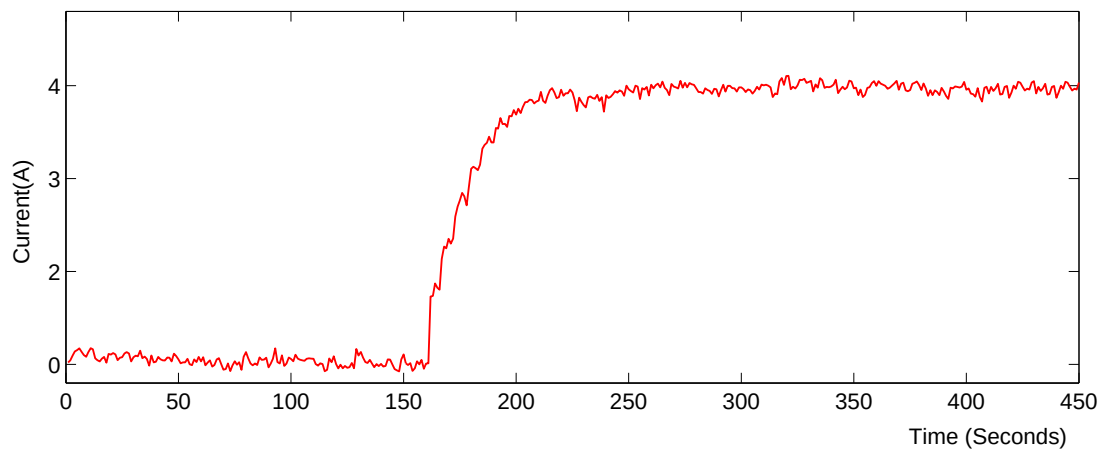


Figure 9.6: UDC LV side current variations during the Start-up state

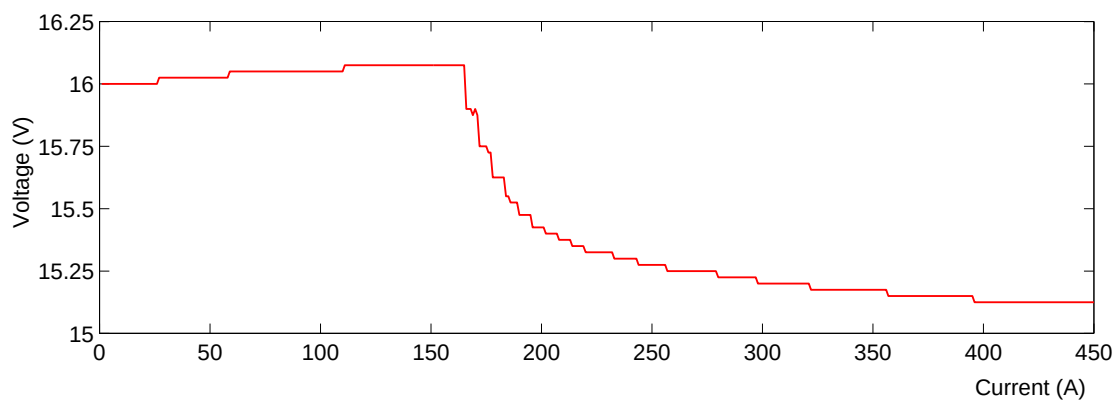


Figure 9.7: UDC LV side voltage variations during the Start-up state

9.2.3 Discussion

The power management system switching sequences during the Start-up state were compared with the simulation results. Initially, the battery currents during the simulation and real time were compared in figure (9.8). The battery was used to power the propulsion system until the fuel cell settling time was reached. In both simulation and experiment curves show that the battery current was gradually increased until 80 seconds by the power management system by boosting the BDC HV side voltage over 24V. The boost mode operation of the BDC increased the DC bus voltage up to 27.5V and the battery current was maximum at 6.4A. After 80 seconds which was the fuel cell settling time, the BDC HV side voltage was gradually decreased and therefore the battery current was decreased. At this state, the UDC was operated in a constant voltage at 24V. When the BDC HV side voltage was lower than the 24V at 155 seconds, the UDC started to supply the power. Figure (9.9) shows the variation of the fuel cell currents during the Start-up mode of the simulation model and the real time emulation. In simulation, the fuel cell current suddenly stepped up into the higher current due to the sudden change in the PWM signal duty ratio. In the real time system, the PWM signal generator gradually increased the PWM duty ratio and hence the DC bus voltage and the fuel cell current were increased gradually. The simulation and the emulation Start-up sequences were similar to the proposed steps in the figure (6.8) shown in chapter (6). However, in the real time operation, the constant time period between t_1 to t_2 was avoided for the initial battery charging process due to the initial charge of the battery being over 12V. The Start-up state experiment results show that the power management system performances were similar to the simulation results and performed according to the proposed power management algorithm steps.

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

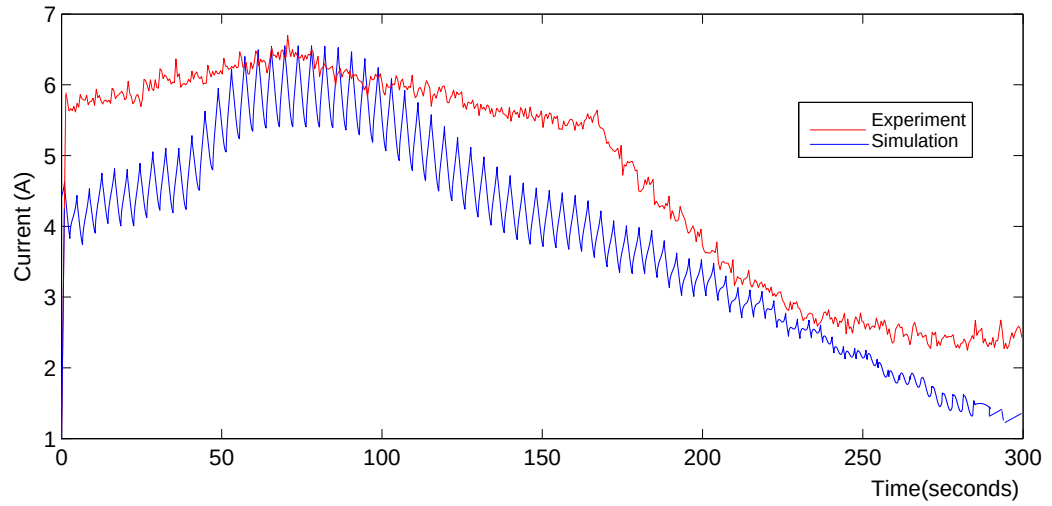


Figure 9.8: Battery current comparison during the Start-up state

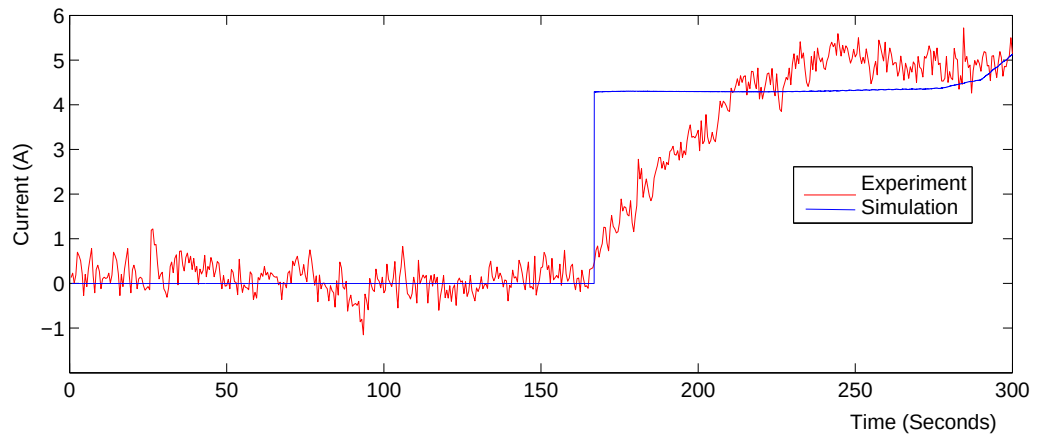


Figure 9.9: Fuel cell current comparison during the Start-up state

9.3 Experiment (2): High Power and Charging Power States

Test

The high power state and the charging power state were tested in this experiment to verify the power management system performances. In the high power and the charging power states, both the primary and the secondary power sources involved in the power sharing process. The current and the voltage changes in the primary and the secondary power sources were measured and compared with the simulation results.

9.3.1 Procedure

After the Start-up state, the power management system activated the high power state for the UAV take-off mode. Initially, the DC load current was $2.8A$ at $24V$. Then, the high power state was applied by increasing the load power to maximum of $8.7A$. The high power state was maintained 193 seconds time period and switched into the Charging power state. The DC load current was maintained at $3.8A$ during the charging state.

9.3.2 Results

The primary power source and the secondary power source current and the voltage variations were measured. The DC load current was increased from the Start-up state to the High power state at 155 seconds. At High power state, the BDC was in the voltage control mode and the UDC in the current control mode. The BDC regulated its output at $24V$ constant value and the UDC varied the DC bus voltage level by the current control process. The DC bus voltage was varied from $24V$ to $30V$ during the High power state and during the Charging power state the voltage reduced to $24V$.

The battery current and the voltage changes in experiment (2) are shown in figures (9.10) and (9.11). The battery current was increased to $9.2A$ and the battery terminal voltage was reduced to approximately $11.8V$ at the High power state. When the charging mode activated, the BDC changed the operating mode into the buck mode and the battery current flow direction was changed. The battery charging current was $88mA$.

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

As can be seen from the figure (9.11), the battery terminal voltage was gradually decreased due to the continuous discharging of the battery. When the charging power mode was activated, the BDC switched into the buck mode and the battery voltage was gradually increased to 11.95V.

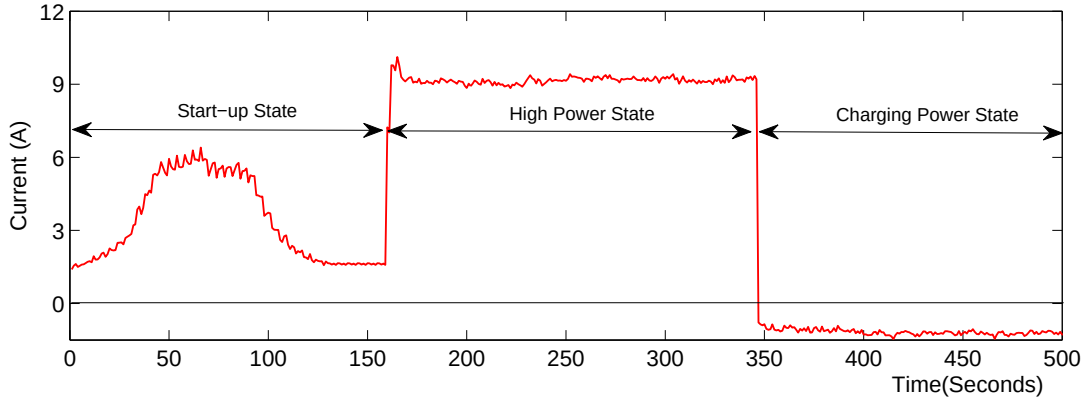


Figure 9.10: Battery current variations during the high and charging states

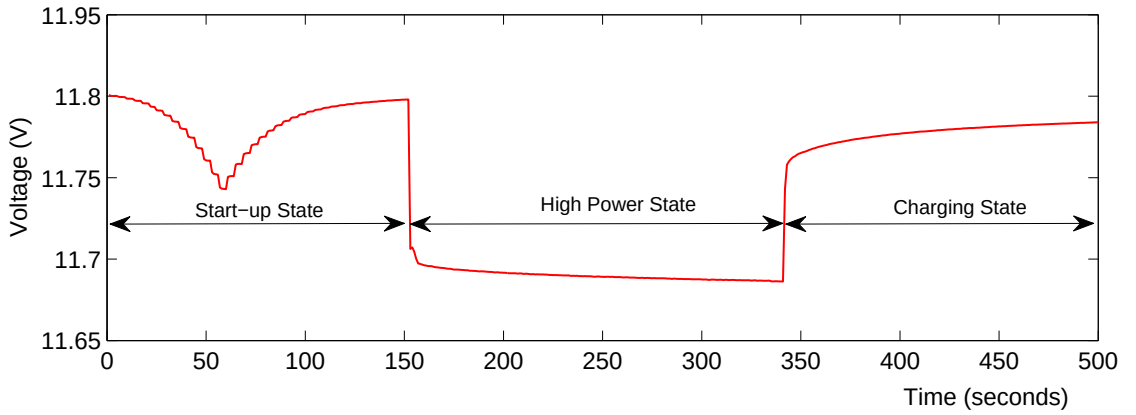


Figure 9.11: Battery voltage variations during the high and charging states

The primary power source's current and the voltage variations during the experiment (2) were measured and illustrated in figures (9.12) and (9.13). During the High power state, the UDC was operated in the current controlled mode and regulated the HV side current output at constant 4.7A. Therefore, the primary power source current was maximized up to 8.5A during the High power state. The voltage was dropped to 13.25V during the High power state and the charging state voltage was 13.9V.

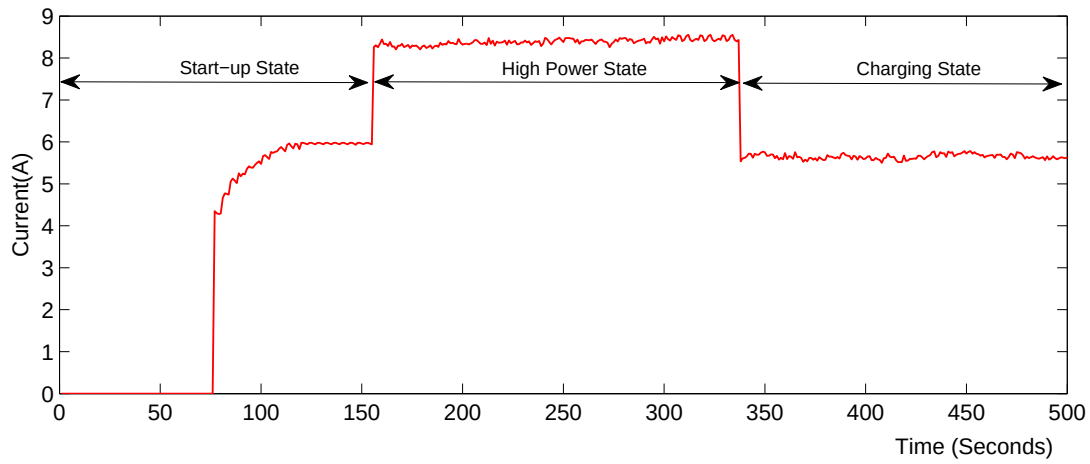


Figure 9.12: Primary power source current variations during the high and charging states

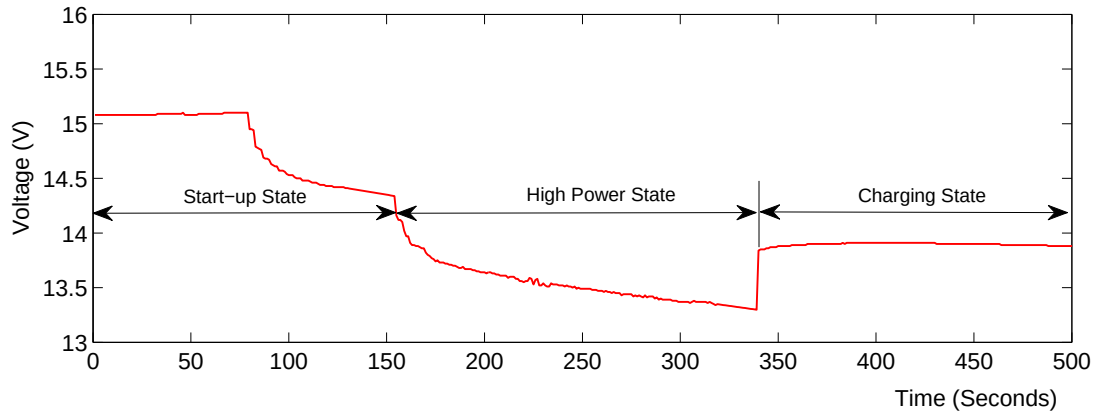


Figure 9.13: Primary power source voltage variations during the high and charging states

9.3.3 Discussion

The main objective of the real time implementation was the verification of the simulation results obtained for power management system state sequence changes. In this analysis, the performance of the power management system during the High power state and the Charging power state were verified by comparing with the simulation results with the real time experiment results. The transition time from the Start-up state to the High power state was extended from 120 seconds to 155 seconds in the experiment and the simulation in order to identify a clear transition stage. For the analysis of the power management system, the experiment (2) and the simulation were conducted by including all the power states such as the Start-up state, High power state and the

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

Charging state. Figure (9.14) shows the battery currents comparison between the simulation and the real time system. Figure shows that the simulated and the experimented results are coincided in each power transition stage. Initially, in the Start-up state, the battery current was increased in both simulated and the real time experimentation and after the fuel cell settling time, the battery current was decreased. For both cases, the High power state was applied after 155 seconds and continued for 190 seconds time period. At 345 seconds, the battery Charging state was activated by the power management system. The battery charging current was $88mA$ during the simulation and the experiment. The battery current was controlled by the BDC and the control decisions were made by the power management system. The results shows that the state transitions of the power management systems in the simulation model and the real time system were happened in the same time sequences as proposed in the power management algorithm.

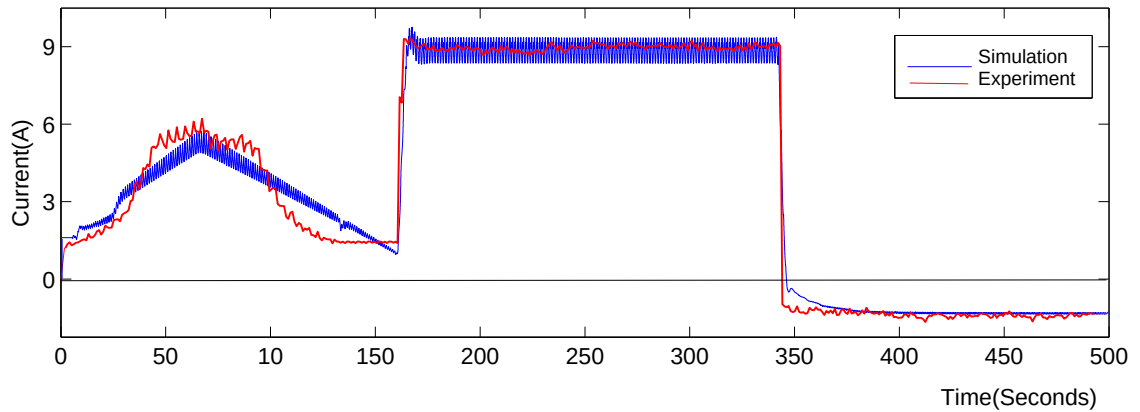


Figure 9.14: Battery current comparison during the High power and Charging states

Figure (9.15) shows the fuel cell currents comparison between the simulation and the experiment. Figure shows that the state transitions were activated as proposed in the power management algorithm. The fuel cell system started to supply the power after 75 seconds and reached to the constant level before the high power state activated. The fuel cell current profile of the simulation shows the smooth variation during the state changes due the slow response of the UDC LV side capacitor. When the battery Charging state was activated, the fuel cell currents were reduced to the initial level

at 6A. The fuel cell current was controlled by the UDC. Based on the current profile obtained in the figure (9.15), the UDC performances can be verified by comparing the simulation and the experimental results.

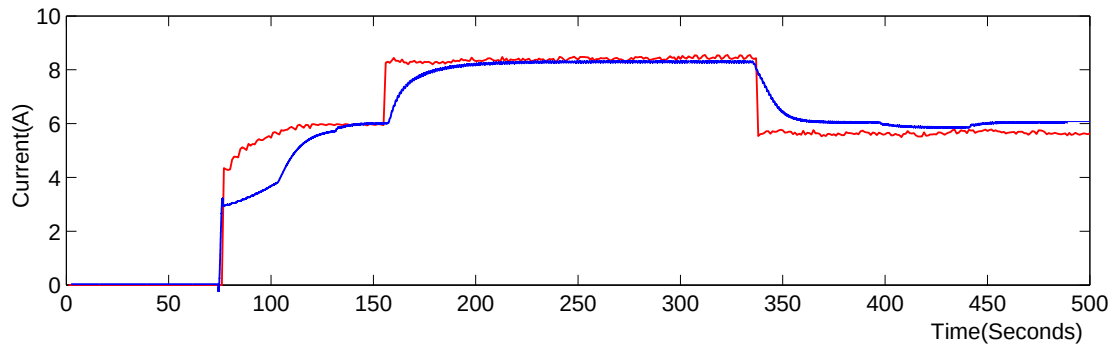


Figure 9.15: *Fuel cell current comparison during the High power state*

9. EXPERIMENTS, RESULTS AND DISCUSSIONS

Conclusion and Future work

This chapter will summarize the research work and will discuss the future prospective of the research findings. The research investigations are focused on the formulating of a new power and energy management architecture for the PEM fuel cell and the Li-Ion battery hybrid electric power system. The power sharing algorithm was developed and implemented in the power electronic interface to validate the expected performances. The PEM fuel cell air supplying system was optimized based on the power management system's decisions and hence minimized the fuel cell system operational losses.

10.1 Power Management

The research objective was to promote the fuel cell and the battery powered hybrid electric system for future unmanned aerial vehicle propulsion applications. Initially, the UAV propulsion power required for the take-off, the climb, the endurance and the maximum velocity were obtained. Then, the PEM fuel cell and the Li-Ion battery specifications were defined according to the propulsion system power requirements. The hybrid system operating power was categorized into the three sections called, the start-up

10. CONCLUSION AND FUTURE WORK

state, the charging state and the high power state. The each power state was consisted of the power management sequences to share the load power between the battery and the fuel cell system. The power management system implemented the state sequences based on the feedbacks received from the battery terminal voltage and the DC bus current. The main objective of the power management system was to obtain the controlled fuel cell current profile. The power electronic interface was consisted of a unidirectional power converter for the fuel cell system and a bidirectional power converter for the battery. The PWM controlled power converters were developed with the voltage control mode and the current control mode to control the power flow of the hybrid system. The PWM signals duty ratios were changed based on the error between the referenced values defined by the power management system and the actual values.

The proposed intelligent power management system was modelled and simulated in Matlab Simpower System toolbox and identified the load power distribution between the power sources. Then, the experimental setup was developed and emulated to verify the proposed power management architecture. As the main part of the hardware development, the bidirectional and the unidirectional power converters were built and controlled by using the micro-controller based embedded system. The power management system was tested in the two missions which had different DC bus current profile to identify the robustness of the hybrid power architecture.

The power management system Start-up state was introduced to initiate the fuel cell system operation by using the secondary power source. Initially, the PEM fuel cell system BOP was powered by the secondary power sources and allocated time for the initial fuel cell reaction. When the fuel cell system started to generate the electricity, the unidirectional converter stepped-up the power supply and the bidirectional converter gradually reduced the Start-up power. During the high power state, the load current was peaked and both the fuel cell and the battery supplied the propulsion power. At this stage, the unidirectional converter and the bidirectional converter were operated in the boost mode. The power management system changed the operating state from the start-up state to high power state during the take-off, initial climb and the maximum velocity. The battery charging mode was introduced the charge the battery during the endurance mode and the cruising mode of the aircraft. The battery charging mode is vital for long endurance UAVs which have sufficient time for battery charging process.

The proposed power management architecture was mainly focused on the control of the fuel cell current as the performance variable that used for fuel cell optimization process.

10.2 Fuel Cell Control

The power management system decided the operating power of the fuel cell system and isolated the fuel cell current from the load current variations. Based on the fuel cell current, the fuel cell air supplying system was controlled as the operational parameter. The fuel cell compressor power optimization technique with the adaptive control algorithm were introduced as the part of the investigations of this research. Initially, the optimum pressure ratios of the fuel cell which generated the maximum net power output of the fuel cell were obtained in different current densities. Then, the referenced model was developed to obtain the optimum compressor power as a function of the fuel cell current.

An adaptive control strategy was introduced to control the fuel cell air supplying system as the part of the hybrid system performance optimization process. The adaptive neuro-fuzzy inference controller was integrated into the fuel cell air supplying system to control the compressor motor voltage. The ANFIS controller received the feedback such as battery state of charge and the fuel cell current from the plant and trained fuzzy output which was the compressor motor voltage to achieve the actual compressor power into the optimum value derived in the referenced model. The ANFIS controller consisted of the rule base system with linguistic rules defined for the compressor motor voltage. The Gaussian membership function's variance, mean and the fuzzy output were trained in each time step and hence obtained the optimized fuzzy output for the fuel cell air supply control. As the main advantages of the ANFIS based control architecture, the controller could operate as a combined controller by regulating the plant and tracking the optimality.

The fuel cell system net power output is compared with the optimum compressor power and the constant compressor power. The optimum compressor power configuration showed 2.62 % energy saving than the constant compressor power configuration. The proposed power and energy management system dynamically controlled the

10. CONCLUSION AND FUTURE WORK

hybrid system power flow based on the propulsion power demand. At the same time, the fuel cell controller optimized the fuel cell system energy utilization.

10.3 Potential Future Research

As the developing concept of the more electric aircraft, the future UAVs will be potentially propelled by the permanent magnet brushless DC motors with the electric power sources. The optimized aircraft in terms of the aircraft design or the aircraft performances will be needed to expand the electric aircraft concept. In this research, the UAV power profile was obtained by considering the basic aerodynamics derivations. However, the aircraft design is needed to optimize by considering the fuel cell and the battery installations into the airframe. Therefore, the vast research potentials can be identified in the future electric aircraft design process.

The electric propulsion system described in this research mostly used the commercially available components such as the brushless motor, the PEM fuel cell and the Li-Ion battery. The hybrid system components are needed to be optimized for the electric aircraft propulsion applications. For an example, a cylindrical fuel cell system might be an advantage for the electric aircraft design process. Therefore, the electric propulsion system components are needed to be optimized in terms of the operational performances or the geometrical performances only considering the electric powered aircraft.

In the electric aircraft, the throttle command given by the pilot is directed to the brushless DC motor controller. It has been assumed that the electric UAV controller is operated similar to the gasoline engine powered UAV's controller. In the fuel cell powered UAVs, the motor control techniques are need to be developed for the electric aircraft applications. The control analysis related to the throttle command and the motor parameters such as the torque and the speed are required to improve for the greater propulsion characteristics.

The proposed power management algorithm included all the possible power state during the UAV mission. However, this hybrid power system can be further developed by introducing a supercapacitor bank as another transient power source. Multiple power sources control architecture with the improved power splitting sequences can be developed for the electric aircraft application.

The adaptive controller developed for the air supplying system control is verified only in the simulation environment. The real-time implementation of the ANFIS controller will be a challengeable task with the available microcontroller technology. The ANFIS controller processing speed is slow due to the back-propagation and the error minimization algorithms. Therefore, the high speed micro-controllers are needed to emulate the ANFIS control architecture in the real time applications.

The electric propulsion system performances can be improved in the real time environment when the proposed power management system and the ANFIS control architecture are implemented in the microcontrollers which have high processing speeds. As the further development of the electric propulsion system, the advanced power electronic interfaces with the modern power converting devices need to be employed in the hybrid electric configuration.

10. CONCLUSION AND FUTURE WORK

Appendix A

A.1 Maximum Lift Coefficient

From reference [3], NACA 23012 airfoil maximum lift coefficient is obtained as 1.8. During the takeoff, the flap angle is turned to 45^0 and as the result of that maximum lift coefficient increased by 0.9. For the efficient cruise, the aircraft aspect ratio should be greater than 5. Therefore, three dimensional effect caused by the aspect ratio reduces the lift coefficient ($C_{L_{max}}$) by 90% [3]. During the take-off period, the NACA 23012 airframe maximum lift coefficient $C_{L_{max}}^{tf}$ is obtained in A.2:

$$C_{L_{max}}^{tf} = 0.9(1.8 + 0.9) \quad (\text{A.1})$$

$$C_{L_{max}}^{tf} = 2.43 \quad (\text{A.2})$$

A.2 Wing loading

Wing loading (W/S) of the aircraft is depended on the stall speed (V_{stall}) and the air density (ρ_∞) [3]. By substituting the air density at sea level $\rho_\infty = 1.225 \text{ kg/m}^3$ and the aircraft stall speed $V_{stall} = 8 \text{ m/s}$ to the (A.3), the UAV wing loading at take-off stage is obtained in (A.4) [3].

$$\frac{W}{S} = \frac{1}{2} \rho_\infty V_{stall}^2 (C_L)_{max} \quad (\text{A.3})$$

$$\frac{W}{S} = 95.25 \text{ N/m}^2 \quad (\text{A.4})$$

Where, S is the wing surface and W is the aircraft weight at any instant.

A.3 Thrust to weight ratio (T/W)

The aircraft total takeoff distance (d) is the summation of the rolling distance (d_g) and the airborne distance (d_a) as shown in (A.1) [3]. When the aircraft is achieved to the lift-off velocity (V_{LO}) which is considered $1.1V_{stall}$ at sea level, the rolling distance is ended up and the aircraft starts to airborne.

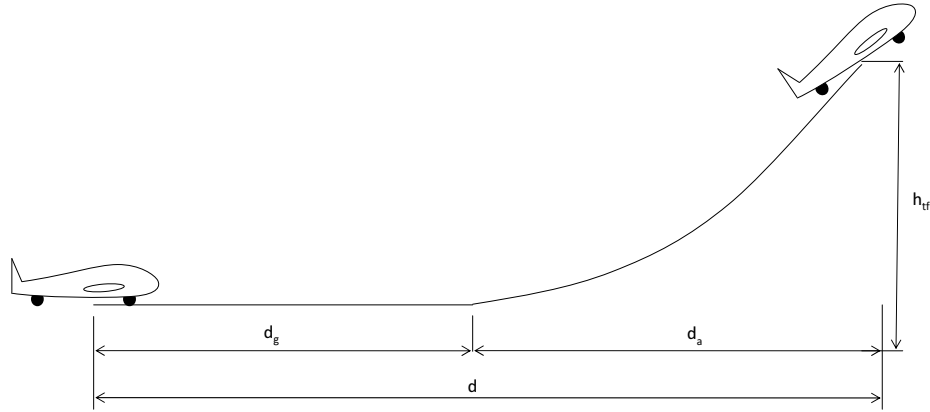


Figure A.1: Aircraft rolling and airborne distance [3]

$$d = d_g + d_a \quad (\text{A.5})$$

The rolling distance of the aircraft (d_g) is depended on the aircraft wingspan (W/S) and the thrust to weight ratio (T/W) [3]. For the propeller driven aircraft, the approximate rolling distance which is described in [3] is shown in (A.6). g is the gravitational force. By substituting the (A.4) and (A.2) into the (A.6), the rolling distance can be described as (A.7) [3].

$$d_g \approx \frac{1.21(\frac{W}{S})}{g\rho_{\infty}(C_{L_{max}})(\frac{T}{W})} \quad (\text{A.6})$$

$$d_g \approx \frac{1.21 \times 95.25 Nm^{-2}}{9.81N \times 1.225kg/m^3 \times 2.43(\frac{T}{W})}$$

$$d_g \approx \frac{3.95}{(\frac{T}{W})} \quad (\text{A.7})$$

The flight path during the airborne distance is shown in figure (A.2) [3]. R is the flight path radius and h_{tf} is the aircraft altitude to clear the obstacle.

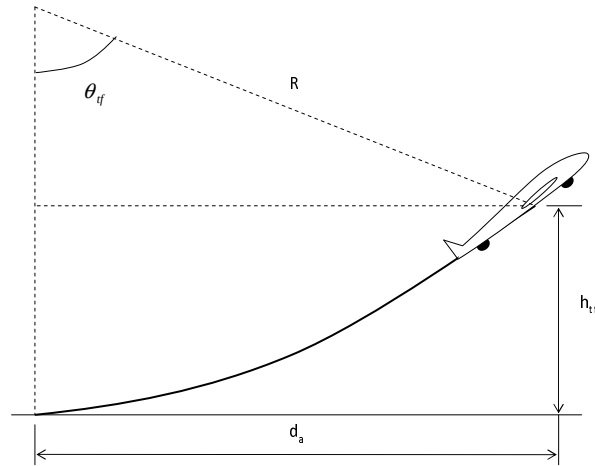


Figure A.2: Flight path radius [3]

In [3], the flight radius R is derived as a function of the takeoff stall speed .

$$R = \frac{6.96v_{stall}^2}{g} \quad (\text{A.8})$$

$$R = \frac{6.96(8ms^{-1})^2}{9.8N)} \quad (\text{A.9})$$

$$R = 45.4m \quad (\text{A.10})$$

A. APPENDIX A

If the airborne distance to clear the obstacles (h_{tf}) is $1m$, from figure (A.2) the angel Θ is determined,

$$\Theta_{tf} = \cos^{-1} \left(1 - \frac{h_{tf}}{R} \right) \quad (A.11)$$

$$\Theta_{tf} = \cos^{-1} \left(1 - \frac{1}{45.4} \right) \quad (A.12)$$

$$\Theta_{tf} = 12.04^0 \quad (A.13)$$

The flight airborne distance d_a can be expressed as,

$$d_a = R \sin(\Theta_{tf}) \quad (A.14)$$

$$S_a = 45.4 \times \sin 12.4^0 \quad (A.15)$$

$$d_a = 9.4m \quad (A.16)$$

As a performance requirement, the total take-off distance of the aircraft is $20m$. By substituting (A.7) and (A.15) into (A.5), the flight $\frac{T}{W}$ is shown in (A.18).

$$20m = 9.4m + \frac{3.93}{\left(\frac{T}{W}\right)} \quad (A.17)$$

$$\frac{T}{W} = 0.370 \quad (A.18)$$

A.4 Lift to Drag ratio

The aircraft lift to drag ratio is expressed as,

$$\frac{C_L^{\frac{3}{2}}}{C_D} = \frac{1}{4} \left(\frac{3}{K C_{D,0}} \right)^{\frac{3}{4}} \quad (A.19)$$

$$\frac{C_L^{\frac{3}{2}}}{C_D} = 11.43 \quad (A.20)$$



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