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Optimal Energy Management for Electric Aircraft

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ABSTRACT

Current technological advances in aviation are geared towards a more “electric aircraft”; seen as a step towards making the aircraft more efficient, reducing emissions and minimising environmental impact. This thesis investigates the feasibility of using an electric hybrid system consisting of a 1.2KW proton exchange membrane fuel cell (PEMFC), three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter to power a small aircraft. Using this hybrid configuration the desired power for different flight phases could be achieved. The advantage of PEMFCs is their high power density, low volume and light weight. They operate at relatively low temperatures that allow them to start up quickly without a warming up time. The thesis starts with a literature review of fuel cell technology and a description of a simulation model for the hybrid system developed using MATLAB/Simulink. Initial experimental results for model validation and the system components performance characteristics will be presented. The experimental data were obtained using 1.2kW Nexa power module FC.

With regards to the power management aspect, two control strategies have been applied: (1) a traditional (PID) controller was designed and implemented in hardware-in-the-loop to control the battery current via the bidirectional DC/DC converter in the hybrid system, and, (2) replacing the PID controller with a fuzzy logic controller (FLC), because significant time delays were found under PID control. The FLC was implemented to manage the power between two sources in the hybrid system because there are many reports in the literature of successful application of FLC to distribute power between different sources in automotive applications. FLC design was based on the following principle: the PEMFC is the main power supply for the electric engine driving the propeller and it has to be operated at optimal efficiency. In the case that the fuel cell cannot completely meet the power demands in any of the flight phases, the battery will provide a short power burst demand as required. At the same time the FC should keep the battery adequately charged at all times. The controller's input variables are the electric engine power demand and battery state of charge represented by the battery voltage. The output variable is the bidirectional DC/DC converter output power. The use of a FLC allowed the system to operate at an optimal efficiency, satisfying the aircraft's power demand during different flight phases.

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NOTATION

a	Species activity
A	Area (m^2)
c	Mole concentration (mol m^{-3})
c_p	Specific heat capacity (J (kg K)^{-1})
C	Heat capacity (J K^{-1})
e	Magnitude of the charge on one electron (C)
E	Reversible open circuit voltage
D	Diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
$\langle D \rangle$	Effective diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
F	Faraday constant (C mol^{-1})
$\bar{g}_f$	Gibbs free energy (kJ mol^{-1})
h	Mass specific enthalpy (W kg^{-1})
h_f^0	Mass specific enthalpy of formation (W kg^{-1})
$\bar{h}_f$	Molar enthalpy (J mol^{-1})
$\dot{H}$	Enthalpy flow rate (W)
I	Current (A)
I_b	Base current (A)
I_c	Collector current (A)
j	Current density (A m^{-2})
K	Valve coefficient (kg (bar s)^{-1})
K_h	Heat transfer coefficient
m	Mass (kg)
mf	Membership function
$\dot{m}$	Mass flow rate (kg s^{-1})
M	Molar mass (kg mol^{-1})
n_d	Electro-osmotic drag coefficient
n_{fc}	Number of cells
N	Molar flux ($\text{mol s}^{-1} \text{m}^{-2}$)
p	Pressure (N m^{-2})
P	Power (W)
$\dot{Q}$	Heat flow rate (W)
R	Ideal gas constant (J (mol K)^{-1})
R	Resistor (Ω)
s	Fraction of liquid water volume to the total volume
s_{im}	Level of immobile saturation
S_r	Reduced liquid water saturation
$\bar{S}$	Molar entropy ($\text{J mol}^{-1} \text{K}^{-1}$)
t	Time (s)
T	Temperature (K)

U	Internal energy (kJ)
V	Voltage or volume (m^3 or V)

Greek letters

ω	Mass fraction
ω_r	Humidity ratio
x	Polarization curve coefficient
α_1	Flooding experimental coefficient
α_w	Conductivity correction coefficient
γ	Volumetric condensation coefficient
δ	Thickness of diffusion layer (m)
ε	Porosity or emissivity
η	Viscosity ($\text{kg}(\text{m s})^{-1}$)
θ_c	Contact angle ($^\circ$)
λ	Water content or excess ratio
μ	Permeability (m^2) or fuel utilisation coefficient
μ_f	Fuel utilisation coefficient
μ_r	Relative permeability (kg mol^{-1})
ρ	Mass density (kg m^{-3})
σ	Surface tension or Stefan- Boltzmann constant (N m^{-1} or $\text{W m}^{-2} \text{K}^{-4}$)
ϕ	Relative humidity

Subscripts and superscripts

a	Dry air
an	Anode
act	Activation losses
amb	Ambient
anch	Anode flow channel
anGDL	Anode gas diffusion layer
atm	Atmospheric
B	Fuel cell stack body
c	Capillary
ca	Cathode
cach	Cathode flow channel
caGDL	Cathode gas diffusion layer
conc	Concentration losses
conv	Convection
cool	Coolant
d	Derivative
dry	Dry
elec	Electric
evap	Evaporation
fc	Fuel cell
forc	Forced

g	Vapour
gen	Generated
H ₂	Hydrogen
H ₂ O	Water
i	Intergral
im	Immobile
in	Inlet
l	Liquid water
ma	Moisture air
max	Maximum
memb	Membrane
nat	Natural
min	Minimum
N ₂	Nitrogen
0	Initial or reference
ohm	Ohmic losses
out	Outlet
O ₂	Oxygen
p	Pore
P	Proportional
purge	Purge
rad	Radiation
react	Reaction
REF	Reference
s	Supply
sat	Saturation
st	Fuel cell stack

Acronyms

AFC	Alkaline Fuel Cell
ACARE	Advisory Council for Aeronautics Research in Europe
APU	Auxiliary Power Unit
BR&TE	Boeing Research and Technology Europe
CCM	Continuous Conduction Mode
CVC	Cell Voltage Checker
COM	Common or Ground
DAQ	Data Acquisition
DC	Direct Current
DCM	Discontinuous Conduction Mode
GDL	Gas Diffusion Layer
EMF	Electro-Motive Force
FC	Fuel Cell
FLC	Fuzzy Logic Controller
HEV	Hybrid Electric Vehicle
HHV	Higher Heating Value

LHV	Lower Heating Value
LED	Light-Emitting Diode
LCD	Liquid Crystal Display
MCFC	Molten Carbonate Fuel Cell
MPP	Maximum Power Point
MOSFET	Metal Oxide Semiconductor Field-Effect Transistor
NB	Negative Big
NM	Negative Medium
NS	Negative Small
OCV	Open Circuit Voltage
PAFC	Phosphoric Acid Fuel Cell
PB	Positive Big
PC	Personal Computer
PCI	Peripheral Controller Interface
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Positive Medium
PV	Photovoltaic
PI	Proportional-Integral controller
PID	Proportional-Integral Derivative controller
PS	Positive Small
PSIM	Physical Security Information Management
PWM	Pulse-Width Modulation
RL	Resistant Load
RGA	Relative Gain Array
RPM	Revolutions Per Minute
SOFC	Solid Oxide Fuel Cell
STP	Standard Temperature and Pressure)
UAV	Unmanned Aircraft Vehicle
UC	Ultra-Capacitor
VLP	Voltage Loop
ZO	Zero

1 Introduction

1.1 Background and motivation

Conventional aircraft use gas turbines or piston engines for propulsion. Nowadays, there is increasing pressure to reduce the environmental impact of all modes of transport, including air-travel. The aim is to reduce fuel burn and increase efficiency thus reducing CO₂ and NO_x emissions by jet-powered aircraft per passenger km. In addition to this there are also operational restrictions, especially in Europe with regards to aircraft noise and emissions. The aforementioned challenges are driving aircraft manufactures to explore new technologies such as fuel cells (FC) for use in the aviation sector.

Recent technological advancements in aviation show a trend towards the more electrically powered aircraft. The aim is to make the aircraft more efficient and subsequently reduce emissions and the impact on the environment. Fuel cells are considered among the promising technologies since they have demonstrated a high degree of efficiency for automotive applications and are now under consideration for supplying power to the auxiliary power unit (APU) on large commercial aircraft. In 2008, Michelin 20 kW FC system was used by Airbus and its partners on board on Airbus A320 to power the electric motor pump. The motor was connected to the blue hydraulic circuit to operate the aircraft's ailerons and rudder to be moved with other flight control systems during the flight tests [1 - 2]. Regarding smaller aircraft, FCs could potentially power the entire aircraft. In 2008, Boeing successfully performed flight tests of the first small two-seater FC powered airplane [3]. Motor glider of a Super Dimona HK36TTC from Diamond Aircraft Industries was replaced by a proton exchange membrane fuel cell (PEMFC)/ Lithium battery hybrid system. It supplies power to a brushless DC electrical motor to drive a variable pitch propeller. The FC acted as the primary power source with the assistance of a battery during take-off and climb [2 - 4]. In other projects, an initial design of the general aircraft propulsion system for Rapid 200-FC two-seater aircraft was given by G. Romeo and F. Borello [5]. The propulsion system consists of brushless electric motors, inverter, converter, FC and battery. A number of precautions were taken to guarantee the safe operation

of each element and the reliability of the system. EnergyOr Technologies Inc., a leading developer of advanced PEMFC systems, demonstrated a long endurance flight of more than 10 hours of a FC powered, operational unmanned aerial vehicle (UAV). In August, 2011, the aircraft FAUCON H2 (complete with integrated avionics) carried out a predetermined flight plan of 10 hours and 4 minutes with an autonomous landing [6].

Despite such demonstrations of FC technology in aircraft applications, there are still many technical challenges to be addressed before FC can become an integrated component on commercial aircraft. Some of those challenges include increasing FC efficiency, reliability and performance in real flight conditions. The reason being, that for aeronautical applications there are many considerations such as variable pressure, temperature ranges and stringent safety requirements which have to be met [3]. For the integration of FC in aircraft design, two important parameters need to be taken into consideration: power to weight ratio [7], and FC starting up time. Another factor is hydrogen production and storage, hydrogen does not appear naturally. It has to be extracted from another energy source through a reformation of natural gas or electrolysis. The other challenge is the power management of the FC hybrid system, because a FC alone cannot supply sufficient power in transient response. It has to be in hybrid system with other source such as battery or super-capacitor.

Zadeh is credited with introducing fuzzy set theory upon which fuzzy logic (FL) control is based. The fuzzy set theory was first presented as a means of dealing with non-crisp data sets and only later developed as a control methodology. One of the first applications of FL for control was by King and Mamdani (control of a steam engine). Since then FL has been widely applied in control applications. There are many reports in the literature of the successful application of using FL to manage the power between different sources in automotive applications. Therefore using FL controller to manage the power between two sources (FC and battery) on board an aircraft can be seen as step towards more electrically powered aircraft powered sufficiently by FC hybrid system.

1.2 Aims and objectives

The aim of this research is to investigate the feasibility of using an electric hybrid system that consists of a FC and battery to power a light aircraft. The main focus is to develop a simulation model of the FC hybrid system using MATLAB/Simulink, implement advanced control strategies (more specifically the use of fuzzy logic controller) in both simulation and hardware-in-the-loop to manage the power between two sources and maintain the FC operating at optimal efficiency. The practical implementation of such schemes will be investigated using an experimental set-up. The main objectives are as follows:

- Build a simulation model in MATLAB/Simulink of the FC/battery hybrid system.
- Set-up a bench testing experimental facility, check and test each component in the hybrid system to verify results obtained from the simulation.
- Implement a classical PID controller.
- Develop a fuzzy logic controller and integrate it in the hybrid system model.
- Carry-out hardware-in-the-loop testing to assess the performance of the PID and fuzzy logic controllers.
- Test case flight scenarios: Investigate controller power management performance for different flight phases (both in simulation and hardware-in-the-loop).

1.3 Thesis overview

Chapter 2 presents the literature review of FCs technology, basic operations, types and applications. It also reviews proton exchange membrane FCs, focusing on how to calculate their energy and efficiency, their applications and the control strategies used to control them.

Chapter 3 starts with brief review simulation model of PEMFC, and then describes the dynamic model of PEMFC (specifically the Nexa FC system).

The experimental set-up is given in Chapter 4. It covers safety considerations, introduces all hybrid system components and interface between the hardware and the software. The following chapter presents initial experimental results of model validation and performance characteristics of the system components.

Chapter 6 introduces the hybrid propulsion system. The system consists of a 1.2kW PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter and electrical engine.

The energy management and implementation of the control strategies for the hybrid system are presented in Chapter 7. This chapter presents the design and implementation of PID and fuzzy logic based power management controllers for simulation and hardware-in-the-loop.

Chapter 8 presents results and discussion of two case studies with different hybrid system configurations and different flight scenarios. Also, a worst case scenario in case study II is demonstrated. Finally, Chapter 9 covers the conclusions of the work and recommends future work.

2 Fuel Cell Technology

Fuel cells can be considered electrochemical power plants that use hydrogen and oxygen as inputs to produce electricity, with water and heat as outputs. They are efficient, reliable, emission-free, and quieter than hydrocarbon fuel-powered engines. They offer tremendous potential environmental benefits and operational savings. A fuel cell operates like a battery by converting the chemical energy from the reactants into electricity. In the case of the battery, the chemical energy is stored internally, when this energy converted to electricity, the battery must be either recharged or thrown away. The fuel cell produces electricity as long as the fuel (such as hydrogen, natural gas, methanol, gasoline...etc.) and oxidant (air or oxygen) is supplied [7 - 9]. Fuel cells generally consist of two electrodes (an anode and a cathode) separated by an ion-conducting membrane. A single cell gives quit small voltage. For this reason, multiple cells are usually stacked in series or parallel depending on the requirements, to provide more power.

2.1 Fuel cell types

There are many applications requiring different types of fuel cells. The classification of fuel cells depends on their electrolyte material which determines many factors such as the type of chemical reaction, the type of catalysts required, operating temperature and type of the fuel to generate electricity. Table 2-1, summarises five major types of fuel cells, all are based upon the same underlying electrochemical principles, namely: 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).

Alkaline fuel cell (AFC): one of the oldest fuel cell technologies and was the first fuel cell to be used in the USA space program to produce on-board electricity and water. These cells do not need precious metal catalysts at either the anode or cathode and use potassium hydroxide solution as the electrolyte [8], [15]. The operating temperature range for AFCs is typically between 50 °C to 200 °C, but today the latest AFCs can operate at temperature as low as 23 °C. The reaction at the anode is:



In this reaction many electrons are released, pass round an external circuit and reach the cathode where they react, forming new OH^- as in Equation (2.2):



The most significant issue with alkaline fuel cell is that they are very susceptible to contamination by carbon dioxide (CO_2). Thus, it is necessary to purify both the hydrogen and oxygen. This purification process makes alkaline fuel cells very expensive and an unlikely candidate for commercial use on a large scale [8].

Table 2-1. Fuel cell types

Fuel Cell Type	Operation Temperature	Mobile Ion	Applications
Alkaline (AFC)	50-200 °C	OH^-	Used in space vehicles
Proton exchange membrane (PEM)	50-100 °C	H^+	Especially suitable for vehicles and mobile applications, but also lower power CHP systems
Phosphoric acid (PAFC)	220 °C	H^+	Large numbers of 200 Kw CHP systems in use
Molten carbonate (MCFC)	650 °C	CO_3^{2-}	Suitable for medium to large scale CHP systems, up MW capacity
Solid oxide (SOFC)	500-1000 °C	O^{2-}	Suitable for all sizes of CHP systems, 2 Kw to multi MW

Proton exchange membrane fuel cell (PEMFC): also known as the polymer electrolyte membrane fuel cell. It operates at relatively low temperatures, around 80 °C, PEMFCs can deliver high power density (up to 1 Acm^{-2} or higher) and the thinness of the membrane electrode assemblies [8]. More details about PEMFC are presented in Section 2.3.

Phosphoric acid fuel cell (PAFC): uses an inorganic acid as the electrolyte, 100% phosphoric acid (H_3PO_4). The phosphoric acid is contained within a Teflon-bonded silicon carbide matrix. This acid works like a membrane in the PEMFC conducting protons. At low temperatures, the ionic conductivity of phosphoric acid is low,

therefore PAFCs operate at higher temperatures (in comparison with PEMFC) in the range 150-220 °C. They work in a similar way to the PEMFC, platinum (Pt) or Pt alloys are used as the catalyst at both electrodes and the protons migrate through the phosphoric acid electrolyte. PAFCs work at around 42% efficiency in generating electricity and 85% efficiency in co-generation applications in which the heat generated can be usefully used for heating water or generating steam. The other advantage of this fuel cell is that carbon monoxide does not affect the electrolyte or cell performance and can be easily operated with reformed fossil fuels. Because of that PAFCs are more tolerant to impurities in reformat than PEM cells. The disadvantage of PAFCs is that they are typically large, heavy and expensive, because they require an expensive platinum catalyst [13].

Molten carbonate fuel cell (MCFC): uses an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminium oxide (LiAlO_2) matrix [13]. The molten carbonate salt mixture is usually a binary mixture of lithium and potassium or lithium and sodium carbonates. Like solid oxide fuel cell they operate at high temperatures around (650 °C) and can reach an efficiency of 60 %. The advantage of this high temperature operation is that no precious metals need be used as catalysts for the electrodes; alkali carbonates form a highly conductive molten salt with carbonate ions providing ionic conduction thus reducing costs. The reactions at the anode and cathode for molten carbonate fuel cell, when using hydrogen or carbon monoxide as fuel are shown in Figure 2-1.

From the equations shown in Figure 2-1, it can be seen that MCFC require carbon dioxide and oxygen to be delivered to the cathode side, this in turn is converted to carbonate ions, which provide the means of ion transfer between the cathode and the anode; subsequently, the carbonate ions are converted back into CO_2 at the anode. Disadvantages of the MCFCs are mainly associated with durability. Component breakdown and corrosion are an issue because of the high temperatures operation.

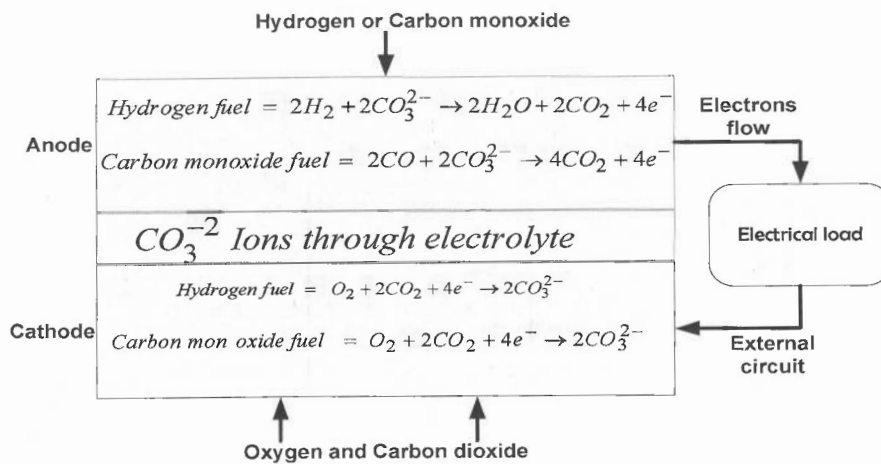


Figure 2-1. Difference reaction of anode and cathode sides of MCFC, when using hydrogen or CO as fuel

Solid oxide fuel cell (SOFC): are solid devices that use a non-porous oxide ceramic material as the electrolyte which is ion-conducting. They can use both hydrogen and carbon monoxide as fuel. Figure 2-2 shows the separate anode and cathode reactions. Solid oxide fuel cells differ from the other fuel cells as they operate at very high temperatures (500-1000 °C), which cancels the need for a precious metal catalyst and allows SOFC to reform the fuels internally, which reduces the cost [13]. SOFCs do not have to be constructed in the typical plate like configuration of other FCs and the expected efficiencies are around 50 % - 60 % in converting fuel to electricity. SOFCs are suitable for large scale stationary power generators that could provide electricity for factories or buildings. Disadvantages of high temperature operation are slow start-up, durability and reliability problems as parts of the fuel cell could break down after repeated on/off cycles.

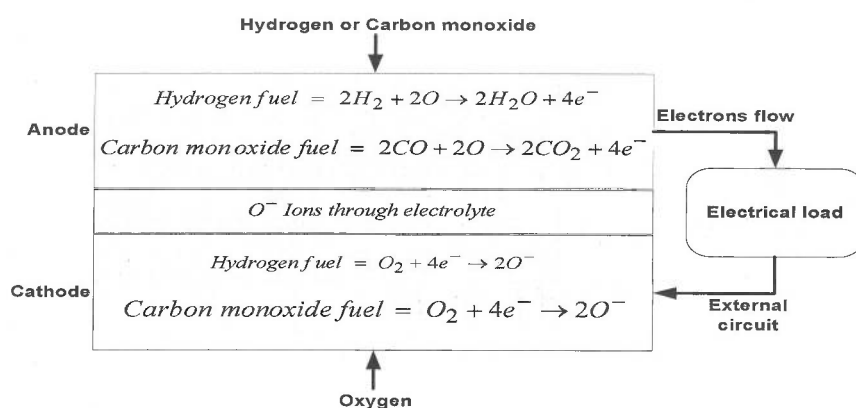


Figure 2-2. Difference reaction of anode and cathode sides of SOFC, when using hydrogen or CO as fuel

2.2 Fuel cell applications

Fuel cell technology has the potential to be used in a broad range of power applications; on a small scale in portable power sources and on a larger scale as an on-site power supply for homes, hospitals, hotels, office buildings and schools. In 1989, a demonstration project used a 5 kW hydrogen and air PEMFC stack to power a home in Albany, capital of New York State. In 1991 Crane Naval Air Base in Indiana installed a 250 kW PEMFC plant for stationary applications [14]. However, PEMFC are considered particularly suitable for use in passenger vehicles. All major automotive manufactures are developing FC stacks for hybrid vehicles. In 1995, PEM cells were being tested in public transport vehicles in Chicago and Vancouver [14] and it now appears that electric vehicles powered by FCs may soon be a viable alternative to battery power [15]. Honda unveiled the first production FCX Clarity FC vehicle at the 2007 Los Angeles Auto Show, with the promise that it would continue to invest heavily in hydrogen FC development, on the grounds that this was seen as a better long term risk than battery powered vehicles. In 2009, Nissan began testing a new FC vehicle and Hyundai promised it would start production of FC vehicles in 2012. Parallel exciting developments are taking place, for example in February 2010 Kit Malthouse, deputy mayor of London said he hoped 150 hydrogen-powered buses would be in operation by 2012 [17].

The military are expressing an increasing interest in FCs as option for aircraft, as they offers the advantages of having a small heat signature and low noise emission, which would be particularly suitable for drone attacks [15], [16]. Commercial aircraft companies such as Airbus and Boeing are committed to research and development of FC technologies for use on aircraft. Diamond Aircraft Industries of Austria built a two seat Dimona motor-glider with 16.3 meter wingspan as a demonstrator airframe. Boeing Research and Technology Europe modified it to include a PEM fuel cell/Lithium battery hybrid system to power an electric motor driving a conventional propeller. The FC provides the power requirements during cruise with lightweight Lithium batteries supplying the extra power required for take-off and climb [10]. In 2000, PEMFCs were chosen to provide night-time power for the solar-powered Helios, an unpiloted aircraft which was intended to fly continuously for up to six months. During the day photovoltaic panels powered the electric motors and electrolyzed water to produce hydrogen. At night the FC drove the motors by converting the hydrogen and oxygen back into water [14]. It was reported in 2008 that an Airbus A320 had successfully tested in flight a FC system that powered the electric motor pump. The motor was connected to the blue hydraulic circle which enabled the aircraft's ailerons and rudder to be moved with other flight control systems in the flight tests. The plans are to develop the FCs, so that they can replace other aircraft systems such as the emergency power system and APU [1].

2.3 Proton exchange membrane fuel cell

The proton exchange membrane fuel cell (PEMFC) was chosen as the type of fuel cell to be used in this research study because it can be very compact which makes it suitable for use on light aircraft which is the main focus of this research project. The basic operation of the hydrogen fuel cell is very simple as shown in Figure 2-3.

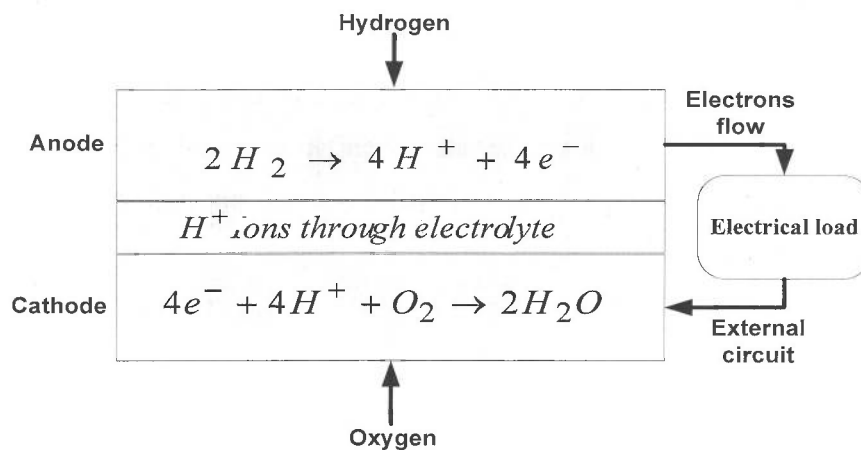


Figure 2-3. Hydrogen-oxygen FC operation

The PEMFC uses a permeable polymeric membrane as the electrolyte. The membrane is very thin and light, and in order to catalyse the reaction, platinum electrodes are used on either side of the membrane. Within the PEMFC unit, hydrogen molecules are supplied at the anode side where the catalyst causes the hydrogen atoms to release their electrons and become ions, as shown in Equation (2.3). The proton exchange membrane only allows hydrogen ions to pass through electrolyte, while the electrons are forced to flow through an external circuit and are utilised as electricity before they reach the cathode side. Then, the hydrogen ions diffusing through the membrane combine with the supplied oxygen (usually from air) and the electrons on the cell's cathode side to form water and heat as illustrated in Equation (2.4). The water must be removed to prevent the cell from being flooded and rendered inoperative, and this is done using the air that flows through the cell. Furthermore, any unused hydrogen and oxygen (air) are exhausted from the cell's anode and cathode outlets, respectively [12], [18].



2.3.1 PEM fuel cell energy and voltage

A fuel cell converts energy stored within a fuel into other useful forms of energy. The total inherent energy of the fuel or any substance is quantified by a property known as internal energy (U). Internal energy is the total of the kinetic energy due to the motion of particles on the atomic and molecular scale [8], [12]. In the case of a fuel cell, it is the Gibbs free energy which is defined as the energy available to do external work (involves moving electrons round an external circuit). The change in Gibbs free energy of formation releases energy. This energy is the difference between the Gibbs free energy of the products and the Gibbs free energy of the reactants as shown in the equation below:

$$\Delta G_f = \Delta G_f \text{ of products} - \Delta G_f \text{ of reactants}$$

In the hydrogen-oxygen fuel cell basic reaction:



The basic reaction is shown in Equation (2.5) where the output is one mole of H_2O , and the inputs are one mole of H_2 and half a mole of O_2 . All quantities are considered in their per mole form [8], [19]. Thus

$$\Delta \bar{g}_f = (\bar{g}_f)_{\text{H}_2\text{O}} - (\bar{g}_f)_{\text{H}_2} - 1/2(\bar{g}_f)_{\text{O}_2} \quad (2.6)$$

The Gibbs free energy changes with temperature and water state (liquid or gas). Table 2-2, shows Gibbs free energy of fuel cell hydrogen reaction shown in Equation (2.5) for different temperatures. The calculation of the Gibbs free energy values is given in **Appendix A**.

Table 2-2. Gibbs free energy, EMF and efficiency of hydrogen FC reaction at various temperatures

Product water form	Temperature (°C)	Δg_f (kJ/mole)	Maximum EMF (V)	Efficiency Limit (%)
Liquid	25 °C	-237.2	1.23 V	83 %
Liquid	80 °C	-228.2	1.18 V	80 %
Gas	100 °C	-225.2	1.17 V	79 %
Gas	200 °C	-220.4	1.14 V	77 %
Gas	400 °C	-210.3	1.09 V	74 %
Gas	600 °C	-199.6	1.04 V	70 %
Gas	800 °C	-188.6	0.98 V	66 %

An explanation of the basic operation of the PEM fuel cell is given in Section 2.3, two electrons travel through the external circuit for every hydrogen molecule used in the reaction and every water molecule produced [8], [19]:

$$-2N_e = -2F \text{ Coulombs}$$

Where: N is Avagadro's number, e is charge on one electron and F is the Faraday constant. If E is the open circuit voltage of the hydrogen fuel cell, then the electrical work done moving this charge round the circuit will be equal to the Gibbs free energy releases Δg_f [8]:

$$\text{Electrical work} = \text{charge} * \text{voltage} = -2FE \text{ Joules}$$

$$\Delta g_f = -2FE$$

$$E = -\frac{\Delta g_f}{2F} \quad (2.7)$$

Equation (2.7) gives the reversible open circuit voltage (OCV) of the cell at STP (standard temperature and pressure), and the maximum open circuit voltage are given in Table 2-2 for the hydrogen fuel cell. The actual fuel cell output voltage can be obtained by starting with thermodynamically predicted fuel cell output voltage

(calculating by using Nernst equation) and then subtracting the voltage losses that occur due to activation losses, ohmic losses and concentration losses see Equation (2.8). The Nernst equation gives the theoretical voltage directly in terms of reactant and product pressures [16] as shown in Equation (2.9).

$$V_{FC} = E_{\text{thermo}} - V_{\text{act}} - V_{\text{ohmic}} - V_{\text{conc}} \quad (2.8)$$

$$E_{\text{thermo}} = E + \frac{RT}{2F} \ln\left(\frac{P_{\text{H}_2} * P_{\text{O}_2}^{1/2}}{P_{\text{H}_2\text{O}}}\right) \quad (2.9)$$

Where, E is reversible cell voltage, R is the universal gas constant, T is temperature (K), F is Faraday's constant, P is relevant partial pressure. The actual output voltage of the fuel cell is always lower than open circuit voltage (OCV) due to unavoidable losses that originate primarily from the following three sources:

Activation losses are due to the delay in the starting up of the chemical reaction, which takes place at the surface of the electrodes. The voltage loss is that required to drive the chemical reaction and to transfer the electrons to or from electrodes, which expressed in the Tafel equation for low temperature fuel cells [8]:

$$V_{\text{act}} = \frac{RT}{2F\alpha} \ln\left(\frac{i + i_n}{i_0}\right) \quad (2.10)$$

The value α is the charge transfer coefficient, i_0 is the exchange current density. This form of the Tafel equation is not prevalent in high temperature fuel cells because the small value of i_n does not significantly change the ratio in the natural logarithm and i_n is usually less than 10.

Ohmic losses are due internal resistances as the current passes through electrodes and electrolyte. In this zone the voltage drop curve is almost linear and is calculated using:

$$V_{\text{ohmic}} = i * r_{\text{int}} \quad (2.11)$$

Where: r_{int} is the internal resistance.

Concentration losses result from depletion of reactants at the surface of the electrodes as the fuel is consumed. If mixture of gases is used to supply the fuel cell, the consumption of one gas causes a small reduction of the partial pressure which directly affect the output voltage [8], [21] is expressed as:

$$V_{conc} = \frac{RT}{2F} \ln\left(1 - \frac{i}{i_1}\right) \quad (2.12)$$

2.3.2 Hydrogen fuel cell efficiency

The efficiency of a fuel cell depends on the power generated. Generating more power means drawing more current, this increases the losses in the fuel cell. In general, lower efficiency as well as voltage drops in the cell is associated with higher current demands. Therefore the voltage of fuel cell relates to its efficiency as shown in Table 2, this can be revealed by adapting Equation (2.7). If all the energy from the hydrogen fuel, heating and calorific values or enthalpy of formation were converted into electricity, then the OCV would be [8]:

$$E = \frac{-\Delta h_f}{2F}$$

$$= 1.48 \text{ volts if using the HHV}$$

Or

$$= 1.25 \text{ volts if using the LHV}$$

The cell efficiency is equal to the cell voltage divided by 1.48V, this number referred to as the higher heating value (HHV).

$$\text{Cell efficiency} = \frac{V_{cell}}{1.48} * 100\%$$

In reality not all fuel supplied to the fuel cell is used; some of it has to be passed through it. A fuel utilisation coefficient is determined by comparing fuel reacted in cell to the fuel input to cell: $\mu_f = \text{mass of fuel reacted in cell} / \text{mass of fuel input to cell}$. Finally, the fuel cell efficiency is given by:

$$\eta_{FC} = \mu_f \frac{V_{cell}}{1.48} * 100\% \quad (2.13)$$

2.3.3 Review control strategies for PEM fuel cell

Many factors affect the efficiency of PEMFCs. These include how effectively the heat generated by electrochemical reactions is removed, the current flowing through the FC, humidity or transport of by-products and reactants. If those could be controlled, the FC would provide such a level of performance, reliability and efficiency that it would replace conventional power sources [22]. A hydrogen/air PEMFC fed with dry gases at the exact stoichiometric ratio should give complete utilization of hydrogen and oxygen. However, for stable regulation of the current in practice, the minimum pure oxygen feed to the cathode was 130% stoichiometric to achieve 100% hydrogen utilization. Methekar et. al., studied the high power density demand in PEMFCs, particularly the input–output transient responses for a distributed parameter model of the PEMFC [23]. The manipulated variables are selected using steady-state relative gain array (RGA) analysis to be the inlet molar flow rates of hydrogen and coolant, and the controlled variables are average power density and solid temperature, respectively. They found that the PEMFC does not exhibit a sign change in the gain of the plant with change in the inlet molar flow rates of hydrogen and coolant. Thus, linear controllers with fixed gain were used to satisfy higher power density demand. It was found that a ratio control strategy was able to overcome the problem of oxygen starvation. Claire and Benziger [22] showed that the output power from a PEMFC can be controlled by restricting the hydrogen feed. Control of the current was possible if the outlets of a self-draining FC were connected to water reservoirs. The internal resistance (and hence current) will vary with the balance of water in the anode flow channel and reservoir.

PEMFC stack temperature, which directly affects the rates of chemical reactions and transport of reactants and water, changes with load current. High temperatures

increase the rates of chemical reaction and could induce thermal stress of the membrane and cathode catalyst and cause degradation. Alternatively, too great a flow of coolant will lower stack temperature and reduce the rates of the chemical reactions so overall efficiency of the system drops. Jong-Woo and Song-Yul have proposed a new temperature control strategy based on a thermal circuit. The thermal circuit consists of a bypass valve, a radiator with a fan, a reservoir and a coolant pump. Classic PI controllers and a state feedback control were used for the thermal circuit. In addition, the heat source term, which is dependent upon the load current, was feed-forwarded to the closed loop [24]. Results show that the temperature of the catalyst was kept within an acceptable value for the duration of the test. The oxygen excess ratio can be maintained at an optimal value by minimizing the influence of temperature variations in the gas flow channel, and the power consumption of the blower reduced by more than 15% by compensation, and 5% by the controlling bypass valve at a multi-step load profile.

Kurz et. al., [25] have studied a control strategy for PEMFC systems using simultaneous impedance measurements made on single cells and have succeeded in running a stack of cells at an optimal operation point by controlling flooding and drying of the cells. It was reported that single cell impedance measurements can detect flooding minutes earlier than seen in the related polarisation curves. It was demonstrated that two impedance measurements, one at a high frequency and the other at a low frequency were able to predict voltage drops due to flooding and drying. Yee-Pien et. al., [26] claim to have successfully simulated and experimentally tested adaptive control with a low power PEMFC. The highly nonlinear, time-varying, distributed parameter FC system of complex electrochemical reactions were approximated using a two-input two-output system, described with four system blocks. The test performed by Yee-Pien et. al. found that the use of adaptive control is effective for PEMFC system subject to the change of system parameters and external disturbances.

Because of the complexity of electrochemical processes in PEMFCs it is hard to tell whether or not the FC is working at its maximum power point (MPP). Zhong et. al., [27] reported a first attempt to trace the MPP using an adaptive MPP tracking controller with an extremum seeking algorithm. The intention was to automatically

maintain the FC working at its MPP. The simulations carried out showed that the control scheme proposed was able not only to follow the MPP but also to solve parallel FC optimization problems, including maximising efficiency. Bordons et. al., [28] have attempted an analysis of possible control strategies for a PEMFC with different operational objectives: maximization of efficiency, prevention of oxygen starvation and tracking of a desired output voltage. Subsequently Bordons and his colleagues developed predictive controllers for each of these cases with consideration of measurable disturbances (load current) constraints. They showed that constrained predictive control was a good means by which to control FC in a number of situations [29].

For the PEMFC Bordons and his team [30] identified the oxygen excess ratio λ_{O_2} and net current as optimal profiles with which to prevent oxygen starvation, minimise fuel consumption and to supply the desired power with the minimum losses. This was achieved by regulating the FC current using a DC/DC switching converter, and controlling the voltage of the air pump. To regulate the DC bus Bordons introduced a capacitor bank which powered the load transients and a control algorithm which matched the power output of the FC to the new steady state. To solve the oxygen stoichiometry control problem of PEMFC, Ali et. al., [31] have used a linear control approach. The controller is based on a Linear Quadratic Regulator/Linear Quadratic Gaussian Regulator strategy that maximises the energy conversion efficiency of the overall system and simultaneously avoids oxygen starvation by regulating the stack oxygen stoichiometry. A feature of the approach is that it requires reduced information to operate. The experimental results obtained from real scenarios demonstrated the effectiveness and feasibility of the proposed approach for both stack current variations and oxygen stoichiometry.

2.4 Chapter summary

The literature review of fuel cell technology, basic operations, types and applications have been presented in this chapter. It also reviews proton exchange membrane FCs, focusing on how to calculate their energy and efficiency, their applications and the control strategies used for their control. The proton exchange membrane fuel cell (PEMFC) was chosen as the type of fuel cell to be used in this research study because of the following advantages:

- It operates at relatively low temperatures, around 80 °C, which allows rapid start-up without a warming up time.
- It can deliver high power density (up to 1 Acm⁻² or higher).
- The thinness of the membrane electrode assemblies gives it the advantage of low weight and volume. Therefore they could potentially be employed in aerospace application, where weight plays an important factor.

3 Fuel Cell Simulation Model

Robust and accurate FC models are needed to simulate the behaviour of complex systems, test control strategies to improve the FC reliability and efficiency by providing optimal solutions; such an approach also saves expense and time [32], [33], [34]. Numerical simulations can also provide the values of the variables that are difficult to experimentally measure [39]. In developing such models knowledge of parameters such as: number of cells in the stack, temperatures of fuel and oxidant, fuel and oxidant pressures and weight fraction of the reactants is needed. For mathematical modelling certain parameters must be known or solvable: for hydrogen, oxygen and water vapour those include mole fraction, molar flow rate, pressure, and velocity; physical and material properties include areas, densities, electrical or ionic conductivity, temperature, thermal conductivity and thicknesses [32]. This chapter will present a review of PEMFC simulation models, and then focus on the dynamic model of PEMFC (specifically the Nexa FC system) used in this project.

3.1 Review simulation model of PEM fuel cell

Most the FC models which have been published are for steady-state conditions. However, interest in the dynamic operation of FCs has been increasing. Reggiani et. al., [34] have developed and presented a nonlinear circuit model for PEMFC which can be used to simulate both steady state and dynamic behaviour of a PEM stack if the values of some of its parameters are changed to correspond to the appropriate operating condition. The parameters were determined through experiments and calculations (such as activation voltage drop, ohmic voltage drop, ohmic resistance). El-Sharkh et. al., [35] have presented dynamic electrochemical simulation model for a 5 kW PEMFC system. In the model assumes the internal resistance and stack temperature to be constant. Later Zhihao et. al., [33] investigated the effects of internal resistance and temperature on PEM power module output characteristics under load variation. They found that internal resistance and temperature have significant effects on both the static and dynamic characteristics of the FC output, and then developed a semi-empirical dynamic model for a Nexa PEM power module taking into account the characteristics of the temperature and the equivalent internal resistance.

Ramos-Paja et. al., [36] introduced a PEMFC dynamic model that was implemented in power-electronics simulation software (PSIM) environment and validated the model using experimental data obtained from a Ballard Nexa 1.2 kW FC. The essential feature of this approach was the interaction of electrical circuit-based models and electrochemical equations. Gao et. al., [37] introduced a dynamic multi-physical FC stack model of a Ballard Nexa 1.2 kW FC. The model is claimed to be suitable for real-time applications in each of the three physical domains: electrical, fluidic and thermal. The FC system auxiliary models are given based on experimental data and the FC stack electrical part is emulated using DC/DC buck converter. The converter is designed to meet the real-fuel cell dynamic responses. Jee-Hoon et. al. [38] have developed computationally efficient thermal and electric dynamic model of a PEMFC for a real-time simulation and verified the model using a Ballard Nexa FC stack. The electrical voltage and thermal dynamics of individual FC layers are included in the model. As well, the stack current and voltage are calculated in emulating the FC stack, taking into account several effects such as fuel and air supplies.

3.2 PEM fuel cell dynamic model description

The dynamic semi-empiric model of Real et al. [39] derived from theory and experimental results for a 1.2kW Ballard PEMFC is used in this research. The model is in four blocks and was developed using MATLAB/Simulink. The blocks represent the air pump, FC stack, cooling fan and hydrogen inlet valve, see Figure 3-1. The block representing the FC stack is sub-divided into three modules: electrochemical, thermodynamic, and fluid dynamics. Experimental data were obtained from a Nexa power module FC system. The experimental data obtained were used as an input to the PEMFC model. The parameters of interest are: ambient temperature, air pump and cooling fan voltages, current demand and anode purge valve status.

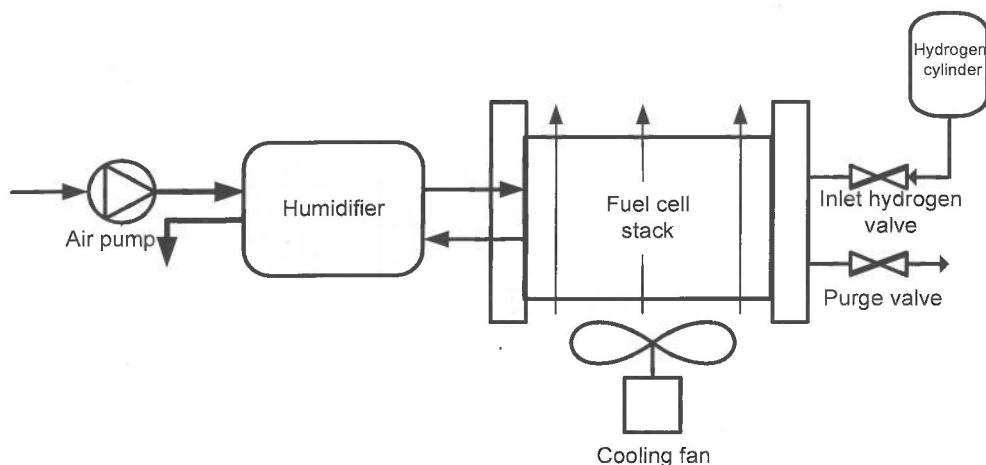


Figure 3-1. The main components of the Nexa FC model

Table 3-1, shows the characteristic times of the FC, where O denotes the order of magnitude. It can be seen that characteristic times for electrochemical dynamics are many orders of magnitude faster than for the fluid dynamic which, in turn, is several orders of magnitude faster than for the temperature and content of liquid water. Therefore electrochemical reaction can be neglected [39], [19].

Table 3-1. Time constants of FC dynamics

Dynamical effect	Characteristic time
Electrochemistry	$O(10^{-19})s$
Fluid-dynamics	$O(10^{-1})s$
Temperature	$O(10^2)s$
Content of liquid water	$O(10^2)s$

3.2.1 Fluid dynamic model

The fluid dynamics model comprises five inter-related sub-blocks, see Figure 5: these are the control volumes of two flow channels, the gas diffusion layers on the cathode and anode, and the transport of chemical species across the membrane. The temperature is everywhere assumed to be that of the stack temperature [39]. The sign convention adopted is that downward flow and flow from left to right is positive, as shown in Figure 3-2.

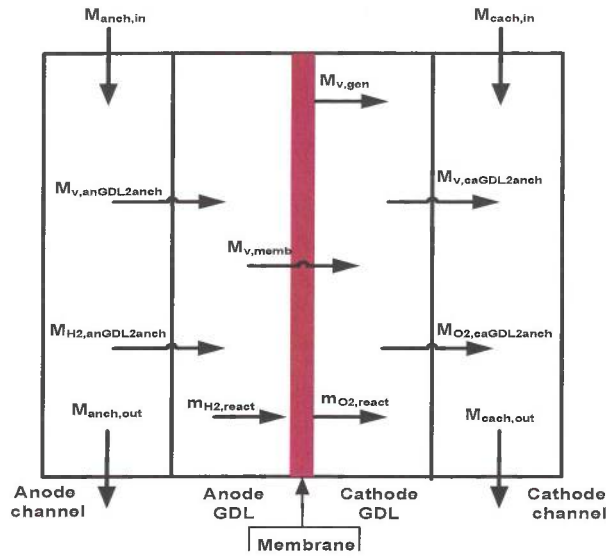


Figure 3-2. Signal criteria [del Real]

In Figure 3-2 the subscripts **an** and **ca** refer to the anode and cathode respectively. The subscripts **in** and **out** refer to flows into and out of the relevant cell respectively. **H₂** to hydrogen, **O₂** to oxygen, **anch** to the anode channel, **cach** to the cathode channel, **GDL** to gas diffusion layer, **caGDL** and **anGDL** refer to cathode and anode gas diffusion layers respectively. In the following section subscripts **evap** refers to evaporation.

3.2.1.1 Cathode flow channel

An air pump supplies flow of inlet air which was conditioned by a humidifier. The initial conditions of air are measured and known: temperature ($T_{cach,in}$), mass flow rate ($m_{cach,in}$) and relative humidity ($\phi_{cach,in}$). A number of simplifying assumptions are made [39], [40]:

- Dry air composition will be assumed to be equal to that of the atmospheric air.
- $P_{cach,in} = P_{cach}$ and the pressure at the end of the channel equals to the atmospheric pressure, $P_{cach,out} = P_{atm}$.
- Nitrogen exchange will be neglected as it is an inert gas.

- The differences in oxygen pressure between the cathode flow channel and the cathode gas diffusion layer are negligible.
- $\dot{m}_{l,cach,in} = 0$, no liquid water carried by the inlet air enters the cathode channel and $\dot{m}_{l,caGDL2cach,in} = 0$, because the membrane does not allow liquid water transport, it only allows gas transport.

All parameters values that used in the flow channel equations are listed in Table 3-2. The inlet air flow is defined as [19], [39], [41]:

$$\dot{m}_{O_2,cach,in} = w_{O_2,cach,in} \frac{1}{1 + w_{r,cach,in}} \dot{m}_{cach,in} \quad (3.1)$$

$$\dot{m}_{N_2,cach,in} = w_{N_2,cach,in} \frac{1}{1 + w_{r,cach,in}} \dot{m}_{cach,in} \quad (3.2)$$

$$\dot{m}_{v,cach,in} = \frac{w_{r,cach,in}}{1 + w_{r,cach,in}} \dot{m}_{cach,in} \quad (3.3)$$

Where:

$$w_{r,cach,in} = \frac{M_v}{M_A} \frac{\phi_{cach,in} P_{sat}(T_{cach,in})}{P_{cach,in} - \phi_{cach,in} P_{sat}(T_{cach,in})} \quad (3.4)$$

The dry air mass fraction equals to the atmospheric air mass fraction:

$$w_{O_2,cach,in} = 0.21 M_{O_2} M_a^{-1}$$

$$w_{N_2,cach,in} = 0.79 M_{N_2} M_a^{-1}$$

$$M_a = 0.21 M_{O_2} + 0.79 M_{N_2} \cong 0.02885 \text{ Kg/mol}$$

The saturation pressure P_{sat} in the cathode channel depends on the temperature T_{cach} and will be calculated using Equation (3.5) [19]:

$$\text{Log}_{10}(P_{sat}) = -1.69 * 10^{-10} T_{ca,in}^4 + 3.85 * 10^{-7} T_{ca,in}^3 - 3.39 * 10^{-4} T_{ca,in}^2 + 0.143 T - 20.92 \quad (3.5)$$

Balancing the mass flow rates into and out of the cathode channel and determining the inlet and outlet flows and the exchange flow between it and the gas diffusion layer, result in the equations shown below [39], [19]. The water condensed inside the

cathode channel is extracted by the water exhaust, so no water accumulates and $dm_{l,cach}/dt = 0$:

$$\frac{dm_{l,cach}}{dt} = \dot{m}_{l,cach,in} - \dot{m}_{l,cach,out} - \dot{m}_{evap,cach} + \dot{m}_{l,caGDL2cach} \quad (3.6)$$

$$\frac{dm_{v,cach}}{dt} = \dot{m}_{v,cach,in} - \dot{m}_{v,cach,out} + \dot{m}_{v,caGDL2cach} + \dot{m}_{evap,cach} \quad (3.7)$$

$$\frac{dm_{O_2,cach}}{dt} = \dot{m}_{O_2,cach,in} - \dot{m}_{O_2,cach,out} - \dot{m}_{O_2,caGDL2cach} \quad (3.8)$$

$$\frac{dm_{N_2,cach}}{dt} = \dot{m}_{N_2,cach,in} - \dot{m}_{N_2,cach,out} \quad (3.9)$$

$$m_{m,cach} = m_{O_2,cach} + m_{N_2,cach} + m_{v,cach} \quad (3.10)$$

The evaporation and condensation dynamics inside the channel are described by two equations: the first one, Equation (3.7) uses a mass flow balance to calculate the evaporation mass flow. The second one is a logical restriction designed to prevent the evaporation of more liquid water than there is available. The value of $\dot{m}_{evap,cach}$ is positive when the steam pressure is smaller than the saturation pressure, thus causing water to evaporate. On the other hand when the water condenses, the value is negative:

$$\dot{m}_{evap,cach} = \min(A_{fc} (P_{sat}(T_{st}) - P_{v,cach}) \sqrt{\frac{M_v}{2\pi R_{st}}}, \dot{m}_{l,caGDL2cach}) \quad (3.11)$$

The next step is to calculate the partial pressures of the different gaseous species inside the channel (in bars), including oxygen, nitrogen and water vapour along with the relative humidity ϕ :

$$P_{O_2,cach} = \frac{RT_{st}}{M_{O_2} V_{cach}} m_{O_2,cach} \quad (3.12)$$

$$P_{N_2,cach} = \frac{RT_{st}}{M_{N_2} V_{cach}} m_{N_2,cach} \quad (3.13)$$

$$P_{v,cach} = \phi_{cach} P_{sat}(T_{st}) = \frac{RT_{st}}{M_v V_{cach}} m_{v,cach} \quad (3.14)$$

The total pressure inside the channel is:

$$P_{\text{cach}} = P_{\text{O}_2, \text{cach}} + P_{\text{N}_2, \text{cach}} + P_{\text{v}, \text{cach}} \quad (3.15)$$

Finally, supposing that all liquid water on the surface of the channel is dragged out by the air circulating across the cathode flow field, the outlet mass flows will be defined as:

$$\dot{m}_{\text{ma}, \text{cach}, \text{out}} = K_{\text{cach}, \text{out}} (P_{\text{cach}} - P_{\text{cach}, \text{out}}) \quad (3.16)$$

$$\dot{m}_{\text{O}_2, \text{cach}, \text{out}} = \frac{m_{\text{O}_2, \text{cach}}}{m_{\text{ma}, \text{cach}}} \dot{m}_{\text{ma}, \text{cach}, \text{out}} \quad (3.17)$$

$$\dot{m}_{\text{N}_2, \text{cach}, \text{out}} = \frac{m_{\text{N}_2, \text{cach}}}{m_{\text{ma}, \text{cach}}} \dot{m}_{\text{ma}, \text{cach}, \text{out}} \quad (3.18)$$

$$\dot{m}_{\text{v}, \text{cach}, \text{out}} = \frac{m_{\text{v}, \text{cach}}}{m_{\text{ma}, \text{cach}}} \dot{m}_{\text{ma}, \text{cach}, \text{out}} \quad (3.19)$$

$$\dot{m}_{\text{l}, \text{cach}, \text{out}} = \dot{m}_{\text{l}, \text{caGDL2cach}} - \dot{m}_{\text{evap}, \text{cach}} \quad (3.20)$$

3.2.1.2 Anode flow channel

The equations that model the flows and pressures inside the anode channel are similar to the ones used for modelling cathode channel. The main differences being that the hydrogen is supplied from gas cylinder to the anode side and the hydrogen pressure to the stack is regulate to be maintained at around 1.8 bar. Also the anode flow channel remains in dead end mode most of the time except during water purges. Assuming that dry hydrogen enters the channel and applying mass balance with bearing in mind the signal criteria shown in Figure 3-2:

$$\frac{dm_{\text{l}, \text{anch}}}{dt} = -\dot{m}_{\text{l}, \text{anGDL2anch}} - \dot{m}_{\text{evap}, \text{anch}} - \dot{m}_{\text{l}, \text{anch}, \text{out}} \quad (3.21)$$

$$\frac{dm_{\text{v}, \text{anch}}}{dt} = -\dot{m}_{\text{v}, \text{anGDL2anch}, \text{out}} - \dot{m}_{\text{v}, \text{anGDL2anch}} + \dot{m}_{\text{evap}, \text{anch}} \quad (3.22)$$

$$\frac{dm_{\text{H}_2, \text{anch}}}{dt} = \dot{m}_{\text{H}_2, \text{anch}, \text{in}} - \dot{m}_{\text{H}_2, \text{anch}, \text{out}} - \dot{m}_{\text{H}_2, \text{anGDL2anch}} \quad (3.23)$$

The saturation pressure, partial pressures of hydrogen and steam inside the anode channel can be determined from [19], [41]:

$$\text{Log}_{10}(P_{\text{sat}}) = -1.69 * 10^{-10} T_{\text{an}}^4 + 3.85 * 10^{-7} T_{\text{an}}^3 - 3.39 * 10^{-4} T_{\text{an}}^2 + 0.143 T - 20.92 \quad (3.24)$$

$$P_{\text{v,anch}} = \frac{RT_{\text{st}}}{M_{\text{v}} V_{\text{anch}}} m_{\text{v,anch}} \quad (3.25)$$

$$P_{\text{H}_2, \text{anch}} = \frac{RT_{\text{st}}}{M_{\text{H}_2} V_{\text{anch}}} m_{\text{H}_2, \text{anch}} \quad (3.26)$$

Evaporation dynamics are calculated as in the cathode channel:

$$\dot{m}_{\text{evap,anch}} = \min(A_{\text{fc}} (P_{\text{sat}}(T_{\text{st}}) - P_{\text{v,anch}}) \sqrt{\frac{M_{\text{v}}}{2\pi\pi R_{\text{st}}}}, \dot{m}_{\text{l,anGDL2anch}}) \quad (3.27)$$

The purge time t_{purge} , is the time during which most of the water on the surface of the channel is dragged out by gas flow. When the purge valve is closed $V_{\text{out,open}} = 0$, being positive when the valve is opened. It is calculated as shown below:

$$P_{\text{anch}} = P_{\text{v,anch}} + P_{\text{H}_2, \text{anch}} \quad (3.28)$$

$$\dot{m}_{\text{ma,anch,out}} = K_{\text{anch,out}} * V_{\text{out,open}} * (P_{\text{anch}} - P_{\text{atmt}}) \quad (3.29)$$

$$m_{\text{ma,anch}} = m_{\text{H}_2, \text{anch}} + m_{\text{v,anch}} \quad (3.30)$$

$$\dot{m}_{\text{H}_2, \text{anch,out}} = \frac{m_{\text{H}_2, \text{anch}}}{m_{\text{ma,anch}}} \dot{m}_{\text{ma,anch,out}} \quad (3.31)$$

$$\dot{m}_{\text{v,anch,out}} = \frac{m_{\text{v,anch}}}{m_{\text{ma,anch}}} \dot{m}_{\text{ma,anch,out}} \quad (3.32)$$

$$\dot{m}_{\text{l,anch,out}} = \frac{m_{\text{l,anch}}}{t_{\text{purge}}} \quad \text{if } \dot{m}_{\text{ma,anch,out}} > 0 \quad (3.33)$$

3.2.1.3 Cathode and anode gas diffusion layers model

In the simplest case each gas diffusion layer (GDL) is considering as a unique control volume. The equations that model the phenomena taking place within the layers can be divided into two phases: gaseous phase and liquid phase. The model does not consider nitrogen. The hydrogen and oxygen inside the GDLs assumed to be at the same pressure as in the flow channels. Thus, flow of these two gases between the channels and the gas diffusion layers will be determined by electro-chemical reactions. Table 3-2 lists the values of the parameters used for GDL modelling [39], [40].

Gas phase:

It is commonly known that net diffusion of gaseous species takes place from regions of high concentration to regions of low concentration. The molar concentrations of steam inside each GDL and flow channel (both anode and cathode) are calculated as:

$$c_{v,X,GDL} = \frac{P_{v,X,GDL}}{RT_{st}} \quad (3.34)$$

$$c_{v,X} = \frac{P_{v,X}}{RT_{st}} \quad (3.35)$$

Where:

X can refer to both anode and cathode channels.

Next effective diffusion rate $\langle D_j \rangle$ is determined. This will be a function of the gas diffusion layer porosity [39], [40]:

$$s_j = \frac{V_{lj}}{V_p} \quad \text{For } j = \text{caGDL, anGDL} \quad (3.36)$$

$$\langle D_{v,ca} \rangle := D_v \epsilon \left(\frac{\epsilon - 0.11}{1 - 0.11} \right)^{0.785} (1 - s_{ca})^2 \quad (3.37)$$

$$\langle D_{v,an} \rangle := D_v \epsilon \left(\frac{\epsilon - 0.11}{1 - 0.11} \right)^{0.785} (1 - s_{an})^2 \quad (3.38)$$

Where:

$$\varepsilon = \frac{V_p}{V_{GDL}}$$

s is the fraction of liquid water volume to the total volume.

D_j is the diffusion coefficient.

Molar flows can be calculated in terms of effective diffusivity and concentration gradients, as in Equations (3.39), (3.40):

$$N_{v,ca} = -D_{v,ca} \left(\frac{c_{v,ca}^{cath} - c_{v,ca}^{GDL}}{\delta_{GDL}} \right) \quad (3.39)$$

$$N_{v,an} = D_{v,an} \left(\frac{c_{v,an}^{anode} - c_{v,an}^{GDL}}{\delta_{GDL}} \right) \quad (3.40)$$

Where: δ_{GDL} is the GDL thickness.

Equations (3.41), (3.42) are used to determine steam partial pressure inside both cathode and anode GDLs.

$$\frac{dP_{v,caGDL}}{dt} = RT_{st} \left(\frac{N_{v,gen} + N_{v,memb} - N_{v,ca}}{\delta_{GDL}} + R_{evap,ca} \right) \quad (3.41)$$

$$\frac{dP_{v,anGDL}}{dt} = RT_{st} \left(\frac{N_{v,an} + N_{v,memb}}{\delta_{GDL}} + R_{evap,an} \right) \quad (3.42)$$

Where:

$$N_{v,gen} = \frac{I_{st}}{2FA_{fc}}$$

$$N_{O_2,react} = \frac{I_{st}}{4FA_{fc}}$$

$$N_{H_2,react} = \frac{I_{st}}{2FA_{fc}}$$

$N_{v,memb}$ will be covered in Section 3.2.1.4.

Evaporation flows are modelled as in [39], [40].

$$R_{\text{evap,ca}} = \gamma \frac{P_{\text{sat}}(T_{\text{st}}) - P_{\text{v,caGDL}}}{RT_{\text{st}}} \quad (3.43)$$

$$R_{\text{evap,an}} = \gamma \frac{P_{\text{sat}}(T_{\text{st}}) - P_{\text{v,anGDL}}}{RT_{\text{st}}} \quad (3.44)$$

Where: γ is the volumetric condensation coefficient.

Constraint to prevent the evaporation of more liquid water than is available: If $V_{l,j} = 0$ and $R_{\text{evap},j} > 0$ then $R_{\text{evap},j} = 0$

Where: j refers to either the anode or the cathode.

Flows exchanged between GDLs and flow channels are determined by Equations (3.45) to (3.48).

$$\dot{m}_{\text{H}_2, \text{anGDL}2\text{anch}} = A_{\text{fc}} n_{\text{fc}} M_{\text{H}_2} N_{\text{H}_2, \text{react}} \quad (3.45)$$

$$\dot{m}_{\text{O}_2, \text{caGDL}2\text{cach}} = A_{\text{fc}} n_{\text{fc}} M_{\text{O}_2} N_{\text{O}_2, \text{react}} \quad (3.46)$$

$$\dot{m}_{\text{v,anGDL}2\text{anch}} = A_{\text{fc}} n_{\text{fc}} M_{\text{v}} N_{\text{v,an}} \quad (3.47)$$

$$\dot{m}_{\text{v,caGDL}2\text{cach}} = A_{\text{fc}} n_{\text{fc}} M_{\text{v}} N_{\text{v,ca}} \quad (3.48)$$

Liquid phase:

First of all the reduced liquid water saturation is modelled in Equation (3.49) for the GDLs of both sides of the cell. Where s_{im} is the immobile water saturation:

$$S_{r,j} = \begin{cases} \frac{s_j - s_{\text{im}}}{1 - s_{\text{im}}}, & \text{para } s_{\text{im}} < s_j \leq 1 \\ 0, & \text{para } 0 \leq s_j \leq s_{\text{im}} \end{cases} \quad (3.49)$$

Capillary pressure across an interface is a function the curvature of the liquid/gas interface, i.e., the radius in case of a spherical droplet. When liquid and gas are present in a fibrous material the complex pore structure means the curvature of liquid/gas interface is not well defined, nor easy to determine [40]. In such circumstances the Leverett J-function, which relates the capillary pressure to the

reduced liquid water saturation can be used to calculate the capillary pressure ρ_c [39] as following:

$$\rho_c = \frac{\sigma^* \cos \theta_c}{\left(\frac{K}{\varepsilon} \right)^{1/2}} \frac{[.417S_r - 2.120S_r^2 + 1.263S_r^3]}{J(S_r)} \quad (3.50)$$

Where: σ is the surface tension of water at the water/air interface.

θ_c is the contact angle.

In porous media, capillary water flow is always from regions of higher saturation towards regions of lower saturation. The capillary flows of water in GDLs for both anode and cathode channels can be defined as [39]:

$$\dot{m}_{l,caGDL2cach} = \frac{A_{fc} n_{fc} \mu \mu_{rl}}{\eta_l} \left| \frac{d\rho_{c,ca}}{dS} \right| \frac{s_{ca}}{\delta_{GDL}} \quad (3.51)$$

$$\dot{m}_{l,anGDL2anch} = - \frac{A_{fc} n_{fc} \mu \mu_{rl}}{\eta_l} \left| \frac{d\rho_{c,an}}{dS} \right| \frac{s_{an}}{\delta_{GDL}} \quad (3.52)$$

Where: $\mu_{rl} = S_r^3$ is the relative permeability of liquid water, μ is the absolute permeability and η_l is its viscosity. Finally the liquid water volume inside the pores of both the anode and cathode sides is evaluated based on mass balances:

$$\frac{dV_{l,caGDL}}{dt} = \frac{-\dot{m}_{l,caGDL2cach} - \dot{m}_{evap,ca}}{\rho_l} \quad (3.53)$$

$$\frac{dV_{l,anGDL}}{dt} = \frac{\dot{m}_{l,anGDL2anch} - \dot{m}_{evap,an}}{\rho_l} \quad (3.54)$$

Table 3-2. Flow channel, GDLs and membrane model parameters for the Nexa system

Parameters	Value	Description
$\delta_{\text{cach}}, \delta_{\text{anch}}$ (m)	1.5×10^{-3}	Thickness of diffusion layer
n_{fc}	46	Number of cells
A_{fc}^0 (m ²)	110×10^{-4}	The area of a cell
$V_{\text{cach}}, V_{\text{anch}}$ (m ³)	7.59×10^{-4}	Volume of the flow hannels
t_{purge} (s)	0.5	Purge time period
K_{cachput} (kg(bar * s) ⁻¹)	0.01	Cathode valve coefficient
K_{anchput} (kg(bar * s) ⁻¹)	0.0001	Anode purge valve coefficient
K_{anchin} (kg(bar * s) ⁻¹)	0.2	Anode inlet valve coefficient
ε	0.5	GDL porosity
V_{GDL} (m ³)	2.53×10^{-4}	GDL volume
D_v (m ² /s)	34.5×10^{-6}	Vapor diffusivity
δ_{GDL} (m)	0.5×10^{-3}	GDL thickness
γ (s ⁻¹)	0.9×10^3	Volumetric condensation coefficient
s_{im}	0.1	Immobile saturation
σ (N/m)	0.0644	Surface tension
θ_c (°)	120	Contact angle
μ (m ²)	2.55×10^{-13}	Absolute permeability
η_l (kg(m * s) ⁻¹)	0.000405	Water viscosity
ρ_l (kg/m ³)	978	Density of water
α_w	15	Experimental conductivity correction coefficient
δ_{memb} (m)	35×10^{-6}	Membrane thickness
$\rho_{\text{memb,dry}}$ (kg/m ³)	2×10^3	Dry membrane density
$M_{\text{memb,dry}}$ (kg/mol)	1.1	Dry membrane molecular weight

3.2.1.4 Polymer electrolyte membrane model

The membrane does not allow the passage of liquid water but does permit gas diffusion so hydrogen, oxygen, steam and nitrogen can be exchanged across the membrane. Nitrogen flow in the direction of the anode is negligible due to its very slow dynamics (it drags during purging) and also nitrogen is an inert gas. The molar flow across the membrane which used in Equations (3.41) and (3.42) will be calculated by using mass transport principles and membrane properties as published in [39], [40], [42] and [43]:

$$N_{v,memb} = n_d \frac{j}{F} - \alpha_w D_w \frac{c_{v,ca} - c_{v,an}}{\delta_{memb}} \quad (3.55)$$

Where: j is fuel cell current density ($j = \frac{I_{st}}{A_{fc}}$), n_d is the electro-osmotic drag coefficient, D_w is the membrane vapour diffusion coefficient, and δ_{memb} is the membrane thickness. α_w is experimental parameter which corrects the possible deviations of the experimental values obtained from the literature which might be in error due to being based on older membranes. The water concentration $c_{v,j}$ of the both cathode and anode in the electrode are calculated as [39]:

$$c_{v,j} = \frac{\rho_{memb,dry}}{M_{memb,dry}} \lambda_j \quad (3.56)$$

Where $\rho_{memb,dry}$ is the membrane dry density, $M_{memb,dry}$ is the dry membrane molecular weight and λ_j calculate as:

$$\lambda_j = 0.043 + 17.8a_j - 39.85a_j^2 + 36a_j^3$$

Where a_j is equal to ϕ_{jGDL} , which is the relative humidity of the gas inside the GDLs. Next the mass diffusivity of water vapour through the PEM membrane is defined as a piece-wise linear approximation [39] as:

$$D_w = D_{\lambda,j} \exp\left(2416\left(\frac{1}{303} - \frac{1}{T_{st}}\right)\right) \quad (3.57)$$

Where: $D_{\lambda,j}$ is the corrected diffusivity coefficient.

$$D_{\lambda,j} = \begin{cases} 10^{-10}, & \lambda_j < 2 \\ 10^{-10}(1+2(\lambda_j-2)), & 2 \leq \lambda_j \leq 3 \\ 10^{-10}(3-1.67(\lambda_j-3)), & 3 < \lambda_j < 4.5 \\ 1.25 \cdot 10^{-10}, & \lambda_j \geq 4.5 \end{cases}$$

3.2.2 Electrochemical model

The polarization curve presents the voltage supplied by the cell in terms of the current density $j = \frac{I_{st}}{A_{fc}}$. All of electrochemical equation terms, which describe the polarization curve in Equation (3.60) are presented in novel way for optimising and simplifying its formulation. As a result the polarization curve is adapted to the corresponding experimental data by a direct algebraic algorithm [39]. There are many factors that influence the polarization curves, of which main factors are current, reactant partial pressures, temperature and amount of condensed water. The electrical equation model based on the following assumptions:

- Distinction between temperature, oxygen and hydrogen pressure influences.
- Voltage variations near a nominal temperature T_{st}^0 are assumed linear. In fact the experimental data shows that linear range covers almost all the normal operational range of the stack.
- Changes in reactant partial pressures generate logarithmic voltage variations. This logarithmic tendency is more important during start up and shut down stages, when reactant partial pressures are outside of the nominal operational range. However, notice that linearity can be assumed near the nominal points $P_{O_2,ca}^0$ and

$P_{H_2,an}^0$. On one hand, this assumption makes the determination of $\frac{\Delta V_{fc}}{\Delta P_{O_2}}$ much

easier. On the other hand, it simplifies the algebraic algorithm used to obtain the parameters. With these assumptions the following equation may be used simulate fuel cell voltage:

$$V_{fc} = \underbrace{x_1}_{V_0} + \underbrace{x_2(T_{st} - T_{st}^0)}_{\frac{\Delta V_{fc}}{\Delta T_{st}}} + \underbrace{x_3(0.5 \ln(P_{O2,ca}) + \ln(P_{H2}))}_{\frac{\Delta V_{fc}}{\Delta P}} - \underbrace{x_4(1 - \exp(\frac{-j}{X_5}))}_{V_{act}} - \underbrace{x_6 j}_{V_{ohm}} - \underbrace{x_7 j^{(1+x_8)}}_{V_{conc}} \quad (3.58)$$

$$j = \frac{I_{st}}{A_{fc}} = \frac{I_{st}}{\underbrace{A_{fc}^0 (1 - \alpha_1 m_{l,anch})}_{A_{fc,effctive}}} \quad (3.59)$$

The constraints that the FC voltage is positive or zero ($V_{fc} \geq 0$) and the stack voltage V_{st} is defined as the sum of all individual cell voltage can be written as:

$$V_{fc} = E_{thermo} - V_{act} - V_{ohmic} - V_{conc} \quad (3.60)$$

$$V_{st} = n_{fc} V_{fc} \quad (3.61)$$

The algorithm and experimental parameters used to calculate V_{fc} and V_{st} are those of the research group led by Alejandro J del Real [39], and validated again using our experimental results. The purpose of the algebraic algorithm is to calculate the parameters $X_1, \dots, X_8$. Four experimental points $(P_{ji}, \dots, P_{jy})$ for $j=1, \dots, 4$, define the shape of the polarization curve. Also, the coefficients $\frac{\Delta V_{fc}}{\Delta T_{st}}$ and $\frac{\Delta V_{fc}}{\Delta P_{O2}}$ must be known. The four points are chosen as to divide the polarization curve into three parts, each one corresponding to one of the three voltage drops (activation, ohmic and concentration drops). $\frac{\Delta V_{fc}}{\Delta T_{st}}$ and $\frac{\Delta V_{fc}}{\Delta P_{O2}}$ are experimentally obtained from the operation of the fuel cell stack near the nominal points T_{st}^0 and P_{O2}^0 respectively. All parameters in Equation (3.58) are calculated as below and listed in Table 3-3.

$$x_8 = \frac{1 + P_{4i}^2}{0.25 P_{4i}}$$

$$x_7 = \frac{(P_{4v} - P_{3v}) + (P_{2v} - P_{3v}) \left(\frac{P_{4i} - P_{3i}}{P_{3i} - P_{2i}} \right)}{-P_{4i}^{(1+x_8)} + P_{3i}^{(1+x_8)} \left(\frac{P_{4i} - P_{3i}}{P_{3i} - P_{2i}} \right)}$$

$$x_6 = \frac{(P_{2V} - P_{3V}) - x_7 P_{3i}^{(1+x_8)}}{(P_{3i} - P_{2i})}$$

$$x_5 = \frac{P_{2i} - P_{1i}}{4}$$

$$x_4 = P_{1V} - P_{2V} - x_6 P_{2i}$$

$$x_3 = 2P_{O_2,ca}^0 \frac{\Delta V_{fc}}{\Delta P_{O_2,ca}}$$

$$x_2 = \frac{\Delta V_{fc}}{\Delta T_{st}}$$

$$x_1 = P_{1V} - x_3 (0.5 \ln(P_{O_2,ca}^0) + \ln(P_{H_2,an}^0))$$

Table 3-3. Electrochemical model parameters

Parameters	Value
(P _{1i} , P _{1v})	(0, 1)
(P _{2i} , P _{2v})	(0.06, 0.785)
(P _{3i} , P _{3v})	(0.4, 0.555)
(P _{4i} , P _{4v})	(0.5, 0.35)
P _{O₂,ca} ⁰	0.16 (bar)
P _{H₂,an} ⁰	1.25 (bar)
T _{st} ⁰	308 (K)
ΔV _c /ΔT _{st}	2.93×10 ⁻³ (V K ⁻¹)
ΔV _c /ΔP _{O₂,ca}	7.61×10 ⁻¹ (V bar ⁻¹)
(x ₁ , x ₂ , x ₃ , x ₄ , x ₅ , x ₆ , x ₇ , x ₈)	(1.17, 2.93×10 ⁻³ , 0.24, 0.18, 1.50×10 ⁻² , 0.64, 288.59, 10.00)
α ₁	15

3.2.3 Thermal model

The thermal model represents an air-cooled stack system (1.2 kW Ballard stack), and is taking into account the main terms of the overall energy balance: The energy produced in the chemical reaction of water formation (supposed to be formed as water steam) $\dot{H}_{\text{reac}}$, the energy supplied in the form of electricity P_{elec} and the amount of heat lost by radiation $\dot{Q}_{\text{rad,B2amb}}$, and natural and forced convection $\dot{Q}_{\text{conv,B2amb}}$. This energy balance is given by the differential equation:

$$m_{\text{st}} C_{\text{st}} \dot{T}_{\text{st}} = \dot{H}_{\text{reac}} - P_{\text{elec}} - \dot{Q}_{\text{rad,B2amb}} - \dot{Q}_{\text{conv,B2amb}} \quad (3.62)$$

By integration of T_{st} , the temperature of the FC stack can be found as a function of time [39], [41], [44]. $\dot{H}_{reac}$ the chemical reaction of water formation is given be:

$$\dot{H}_{reac} = \dot{m}_{H_2, reac} \Delta h_{H_2} + \dot{m}_{O_2, reac} \Delta h_{O_2} - W_{H_2O, gen(g)} (h_{f, H_2O(g)}^0 \Delta h_{H_2O(g)}) \quad (3.63)$$

Where:

$$\Delta h_{H_2} = c_{p, H_2} (T_{anch, in} - T^0)$$

$$\Delta h_{O_2} = c_{p, O_2} (T_{cach, in} - T^0)$$

$$\Delta h_{H_2O(g)} = c_{p, H_2O(g)} (T_{st} - T^0)$$

$h_{f, H_2O(g)}^0$ is the mass specific enthalpy of formation of water steam.

c_{p, H_2} is specific heats of the hydrogen.

c_{p, O_2} is specific heats of the oxygen.

c_{p, H_2O} is specific heats of the water.

T^0 is the reference temperature for the enthalpy.

The energy in the form of electric power is:

$$P_{elec} = V_{st} I_{st} \quad (3.64)$$

Because the body of the FC has a temperature greater than its surroundings, heat is lost from the surface as radiation, and natural and forced convection. The radiation is modelled:

$$\dot{Q}_{rad, B2amb} = \varepsilon \sigma A_{B2amb, rad} (T_{st}^4 - T_{amb}^4) \quad (3.65)$$

Where: ε is the emissivity of the surface, $A_{B2amb, rad}$ is the radiation exchange area, and σ is Stefan Boltmann constant ($\sigma = 5.678 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$).

The convections losses, both natural and forced convection are modelled as:

$$\dot{Q}_{conv, B2amb} = \dot{Q}_{conv, B2amb, nat} + \dot{Q}_{conv, B2amb, forc} \quad (3.66)$$

Where:

$$\dot{Q}_{\text{conv},B2\text{amb,nat}} = (h_{B2,\text{amb,nat}} A_{B2\text{amb,conv}})(T_{\text{st}} - T_{\text{amb}})$$

$$\dot{Q}_{\text{conv},B2\text{amb,forc}} = (h_{B2,\text{amb,forc}} A_{B2\text{cool,conv}})(T_{\text{st}} - T_{\text{cool}})$$

$$h_{B2,\text{amb,forc}} = K_{h1} (W_{\text{cool}})^{K_{h2}}$$

All parameters for thermal equations are listed in Table 3-4.

Table 3-4. Thermal model parameters

Parameters	Value	Description
m_{st} (kg)	5	FC stack mass
C_{st} ($\text{Jkg}^{-1}\text{K}^{-1}$)	1100	Specific heat capacity
ε	0.9	Emissivity
$A_{B2\text{Ambrad}}$ (m^2)	0.1410	Area upon which the radiative heat dissipation occurs
$A_{B2\text{Amb}}$ (m^2)	0.0720	Area of the fuel cell's lateral walls in which the natural convection takes place
$A_{B2\text{cool,conv}}$ (m^2)	1.2696	Area of the internal walls separating the cells across which the forced convection occurs
$h_{B2\text{Amb,nat}}$ (Wkg^{-1})	14	Mass specific enthalpy
K_{h1} ($\text{Wm}^{-2}\text{K}^{-1}$)	0.0156	Heat transfer coefficient
K_{h2} ($\text{Wm}^{-2}\text{K}^{-1}$)	1	Heat transfer coefficient
$c_{P,H2}$ (Jkg^{-1}K)	14300	The specific heat capacity of hydrogen
$c_{P,O2}$ (Jkg^{-1}K)	918	The specific heat capacity of oxygen
$c_{P,H2O}$ (Jkg^{-1}K)	2080	The specific heat capacity of water steam
$h_{f,H2O(g)}^0$ (kJ/mol)	-241.82	The mass specific enthalpy of formation of water

3.2.4 Auxiliary components

The auxiliary components of the Nexa power module are an air pump, hydrogen feeding valve and cooling fan, see Figure 4. The air pump that supplies oxygen (ambient air) to the cathode flow channel is modelled by a transfer function, the coefficients of which are found experimentally. The transfer function (commonly used in signal processing, control theory and communication theory) [39] mathematically represent the relationship between the output and input of the pump. The experimental data has been taken from 1.2 kW Nexa fuel cell.

$$y(t) = \frac{0.06229z^2 - 0.0145z}{z^3 - 2.277z^2 + 1.811z - 0.5016} u(t) - 45 \quad (3.67)$$

Where: “z” denotes the shift operator, $y(t) = y(t-1)z$ and “t” stands for the current discrete time instant. $u(t)$ is the air pump voltage, obtained experimentally, $y(t)$ is the air mass flow rate in (kg s^{-1}). The cooling fan is calculated as in Equation (3.68). The amount of air supplied by the fan can be considered as linearly proportional to the control signal of the fan. The model input $u(t)$ is the fan voltage, between 0% and 100% and the model output $y(t)$ is the air flow supplied (kg s^{-1}).

$$y(t) = 36u(t) \quad (3.68)$$

The Nexa power module FC system has both pressure regulators and valves to control the hydrogen inlet and outlet mass flows. In the model the inlet manifold is treated as a simple regulating valve which reduces the high pressure in the hydrogen tank to a more suitable level for the anode channel. The inlet flow of the hydrogen is designed to match the rate of hydrogen consumption in the chemical reaction. The valve state is “1” when open and “0” when closed. The same approach as Del Real [39] to model the inlet and purge valves, and is given by the two equations below:

$$\dot{m}_{\text{H2,an,in}} = K_{\text{anch,in}} v_{\text{in,open}} (P_{\text{anch}} - P_{\text{tank}}) \quad (3.69)$$

$$\dot{m}_{\text{H2,an,out}} = K_{\text{anch,out}} v_{\text{out,open}} (P_{\text{anch}} - P_{\text{atm}}) \quad (3.70)$$

3.3 Chapter summary

A dynamic model for PEM fuel cell was developed and presented in this chapter. It is a semi-empirical model derived from theory and experimental results for a 1.2kW Ballard PEMFC stack. The model consists of four blocks (air pump, FC stack, cooling fan and hydrogen inlet valve) and was developed using MATLAB/Simulink, the model has been validated using a 1.2kW Nexa power module PEMFC stack. It is a control-oriented model that can be used for controller design and the development of optimal operational strategies for FC-based power systems. Chapter 5 will present the experimental results used in the model validation and in assessing the performance characteristics of the FC system. In the following chapter, Chapter 4, the experimental set-up of the hybrid fuel cell model used in this project to obtain the experimental results and also to carry-out the hardware-in-the-loop testing will be presented, covering both system configurations and system components.

4 Experimental set-up

This chapter presents the two experimental set-up configurations developed in this project: The first one is the Nexa system configuration which is shown in Figure 4-1. In this configuration the batteries connected in parallel to guarantee a stable operation of the hybrid system. However, with this configuration, it is not possible to control the power from the battery side. The power delivered to the electrical engine will be from both sources or from only one of them depending on the power demands. Therefore, a bidirectional DC/DC converter was later added to the hybrid system on the battery side to control the current from or to the batteries (charging/discharging). Figure 4-2 presents the architecture of the modified fuel cell-battery hybrid system configuration with the bidirectional converter and three batteries. This configuration is the one used in the test cases (described in details in Chapter 6). The next section will cover the Nexa fuel cell installation and auxiliary components for both of the hybrid system configurations.

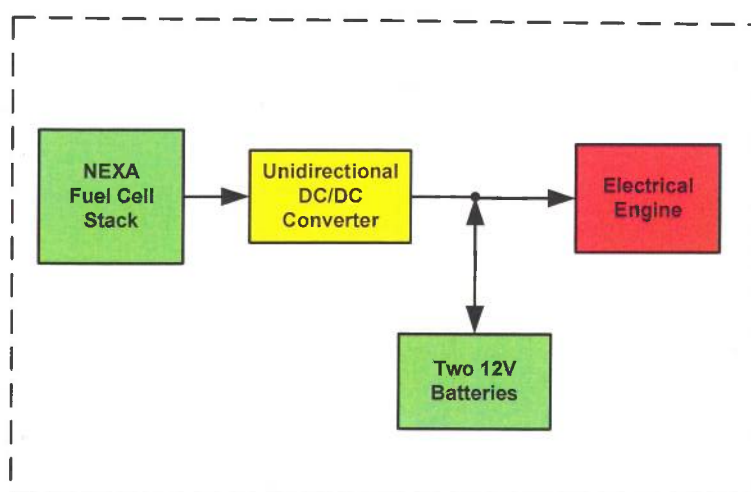


Figure 4-1. The schematic diagram of Nexa FC hybrid system set-up

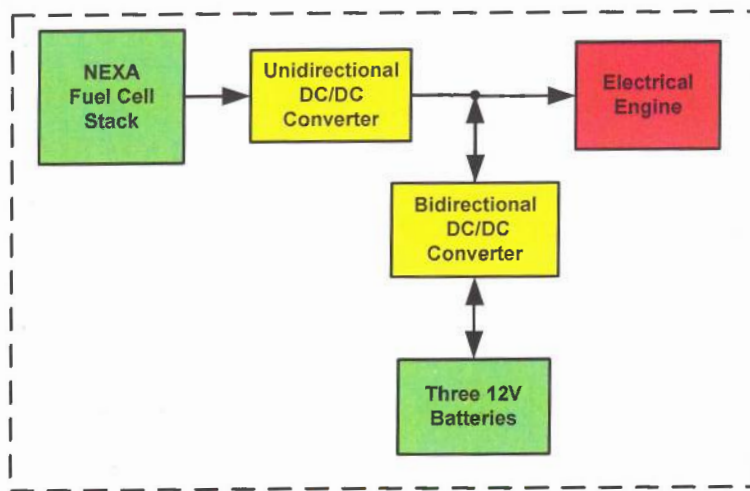


Figure 4-2. The schematic diagram of modified FC-battery hybrid system set-up

4.1 Nexa fuel cell power module set-up

To validate the results from the simulation model, experimental data were obtained from the 1.2kW Nexa power module FC. The Nexa power module is a small, low maintenance and fully integrated system that produces unregulated DC power. It contains a Ballard FC stack, as well as all the ancillary equipment necessary for the FC operation. Ancillary subsystems include hydrogen delivery, oxidant air supply and cooling air supply, onboard sensors monitor system performance. Control board and microprocessor fully automated operation. The Nexa system also incorporates operational safety systems for indoor operation [45].

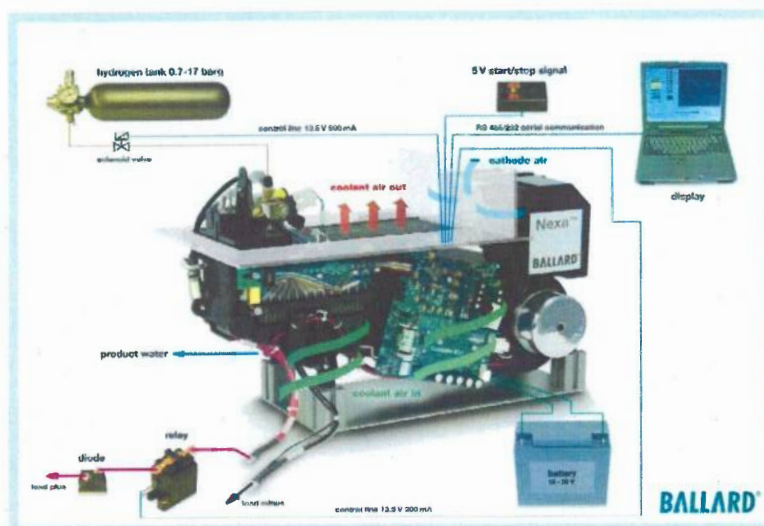


Figure 4-3. Installation of Nexa FC system

Figure 4-3 illustrates the Nexa system installation. The diagram also shows the system boundary and important interface connections to the DC module. Hydrogen, oxidant air, cooling air must be supplied to the unit. Exhaust air, product water and coolant exhaust is emitted. In addition, battery power must be supplied for start up and shut down requirements.

The output voltage level can vary from 43V at no load to about 26V at the full load. The designed operating temperature of the stack is around 65 °C at full load. The stack is composed of 46 cells, each with a 110 cm² membrane. The system is auto-humidified and air-cooled by a small fan. Regarding the hydrogen feed to the FC, the hydrogen is

Table 4-1. Nexa power module specification

Output	Requirement	Quantity
Power	Rated power	1200 W
	Voltage	26V (at rated power)
		22V to 50V (operating voltage range)
	Start-up time	2 minutes
Emissions	Noise	72 dBA
	Water	870 ml/hr
Physical	Dimensions (L*W*H)	56*25*33cm
	Mass	13 Kg
Lifetime	Operating life	1500 hours
	Cyclic life	500
	Shelf life	2 years
Input	Requirement	Quantity
Fuel	Purity	99.99% H ₂ (vol)
	Pressure	70-1720 kPa(g)
	Acceptable impurities	0.01% (vol) (total inert fluids)
		2 ppm (vol) (CO and CO ₂ combined)
		1 ppm (vol) (total hydrocarbon)
		500 ppm (vol) (oxygen)
	Consumption	<18.5 SLPM (fuel consumption at rated power)
Power conditioning	Current ripple (Maximum acceptable current ripple at 120 Hz, with respect to average DC net output current)	24.7% RMS
		35% peak-peak
DC power supply	Voltage	18V to 30V (allowable range of input voltage)
	Power	60 W (drawing power during start-up)
Operating environment	Location	Indoors & outdoors (acceptable locations for use)
	Temperature range	3 °C – 40 °C (Range of acceptable ambient, cooling air and oxidant air temperatures)
	Relative Humidity	0% - 95% (non-condensing)

99.99% pure supplied from a 1460 x 230 mm K-size industrial gas cylinder (65 kilogram) and holding 7200 litres compressed to 175 bar. The hydrogen is not humidified, and the hydrogen pressure to the stack is normally maintained at around 1.8 bar. A PC was used for the acquisition of the measured values, and in order to simulate a variable power demand, the energy produced was delivered to an electronic load. The Nexa specifications are listed in Table 4-1.

Safety considerations

The fuel used in the system is Hydrogen; it is colourless, odourless and flammable substance. It is highly combustible in the presence of oxygen and burns with a colourless flame. For this reason the Nexa system had to be installed in well-ventilated lab area equipped with hydrogen alarm sensors, extractor fan for air circulation in the lab and for safety during FC operation. Figure 4-4 shows Nexa power module FC system set-up.

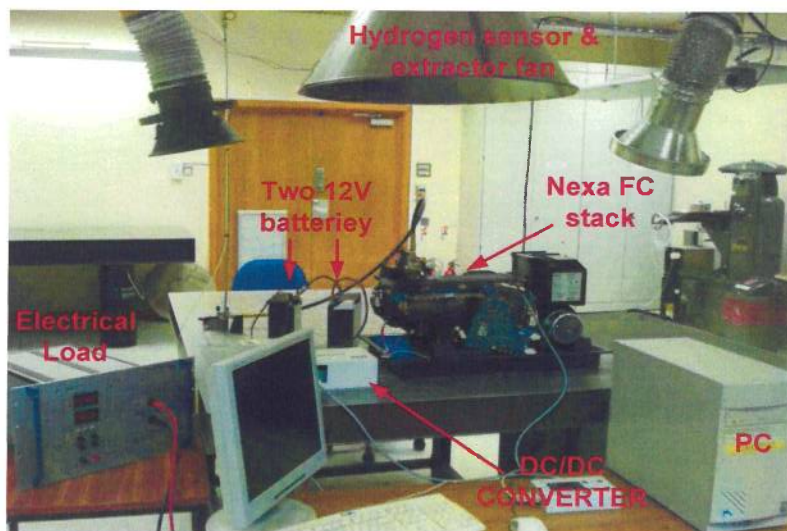
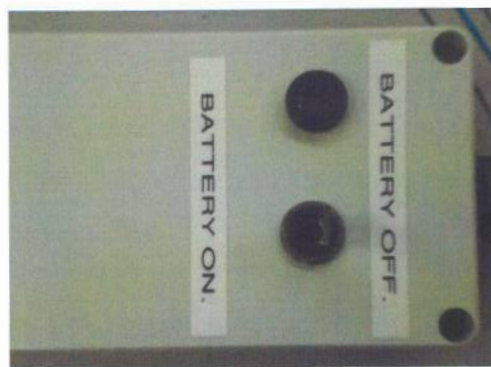


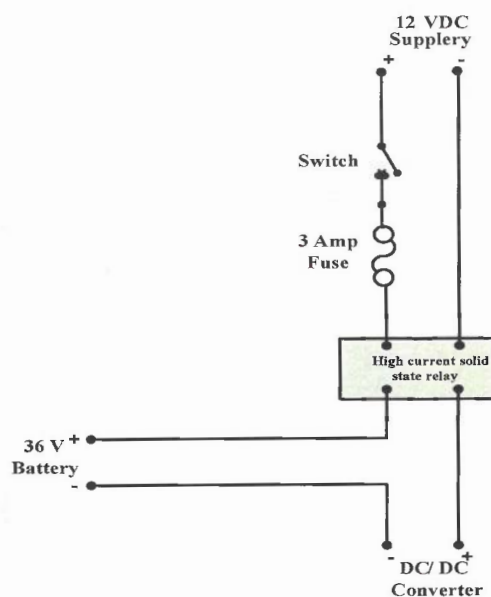
Figure 4-4. Experimental set-up at Cranfield University

The Nexa power module has automatic provision to ensure operator safety and prevent equipment damage. When an unusual or unsafe operating condition occurs a warning or alarm sounds, depending on the severity. The Nexa power module employs the following monitoring and shut down mechanisms at all times.

- FC operating parameters are continuously monitored to ensure they stay within desired limits (FC stack operating temperature, FC stack current, output voltage and fuel supply pressure) Warnings and shut down alarms are implemented on each of these parameters.
- A Cell Voltage Checker (CVC) system continuously monitors the operation and performance of individual cell pairs. The presence of a failing cell will cause the Nexa system to shut down.
- A hydrogen leak detector is included within the fuel delivery subassembly. The Nexa system will shut down automatically if a hydrogen leak is detected.
- The Nexa power module comes equipped with an oxygen sensor for measuring ambient oxygen concentrations. The power module shuts down automatically when low ambient oxygen concentration is measured.



(a)



(b)

Figure 4-5. (a) on/off switch, (b) its electrical circuit

In addition, an ON/OFF switch was installed between the battery side and the main circuit of the fuel cell. Figure 4-5 shows the electrical circuit of the switch which connects the battery in parallel to the rest of the system. The switch consists of on/off switch, fuse and high current state relay. When the switch is engaged the 12 VDC energises the high current solid state relay, in turn closing the loop between the 36V battery and the DC/DC converter. The switch serves two purposes:

- Safety, when connecting/disconnecting the battery for charging/discharging.
- Used to disconnect the battery from the system, to test the FC dynamic response and performance.

4.2 DC/DC unidirectional converter

DC/DC converter BSZ PG 1200 model produced by Isle ® especially for Nexa FCs is used as a unidirectional converter, and is shown in Figure 4-6 (a). The DC/DC converter generates a PWM signal that controls a MOSFET half-bridge. This half-bridge acts as a synchronous buck converter. This topology assures the high efficiency of the converter. DC Power input is heavily filtered so that electromagnetic interference EMI does not affect the fuel cell.

The output voltage is filtered before going out to the load terminals. To prevent back flow of current from battery to fuel cell return protection is provided, controlled by an integrated micro controller. The converter's specifications are listed in Table 4-2. Figure 4-6 (b) shows the Nexa system control unit with the ON/OFF system start up/shutdown buttons and display.



Figure 4-6. (a) Unidirectional DC/DC BSZ PG 1200 converter, (b) Nexa system on/off control unit

Table 4-2. Unidirectional DC/DC converter specification

Output voltage range	11V-15V / 22V-30V
Accuracy of output voltage	2%
Nominal output current	100A/50A
Maximum output current	110A/55A
Maximum output power	1200W
Maximum output current ripple	2%
Operating input voltage range	26VDC-48VDC
Maximum input voltage	50V
Minimum voltage drop input to output	2V
Power consumption standby	2W
Ambient temperature	0°C...40°C
Efficiency	96% (24V)
Short-circuit proof	Yes
Thermal protection	Internal 80°C
Mechanical dimensions (H x B x T)	(320 x 14 x 80) mm

4.3 DC/DC bidirectional converter

Figure 4-7 shows the high performance step down DC6350F-S converter from Zahn Electronics. This is a two quadrant (sourcing and sinking current), maximum converter current and power are 50A and 1600W, respectively, crystal controlled, dual Half H Bridge, configured in a buck topology programmed for Voltage Loop (VLP). It is a compact, self contained unit with its own power supply, input and output power filter. Power to the unit is from a DC supply, fuel cell or battery. Each half bridge has 10 transistors in parallel on the top and 10 transistors in parallel on the bottom. Faster response can be achieved because the switching frequency is 31,250Hz. The temperature of the unit is monitored and in the event of an excessively high ambient temperature, then the current to the load is reduced automatically to hold the transistor temperatures to a safe level [46].



Figure 4-7. Bidirectional DC6350F-S converter

4.4 Current sensor technology

The Hall Effect is an application of electromagnetic induction: consider a simple rectangular plate of conducting material carrying a steady current from left to right as shown in Figure 4-8 (a). There is no measurable voltage in either direction perpendicular to the flow. Now apply a magnetic field perpendicular to the flow. It is found that a voltage will be generated perpendicular to both the direction of the current and the magnetic field. The presence of the magnetic field distorts the electron flow which becomes uneven and creates a potential difference across the plate's faces as shown in Figure 4-8 (b) [47].

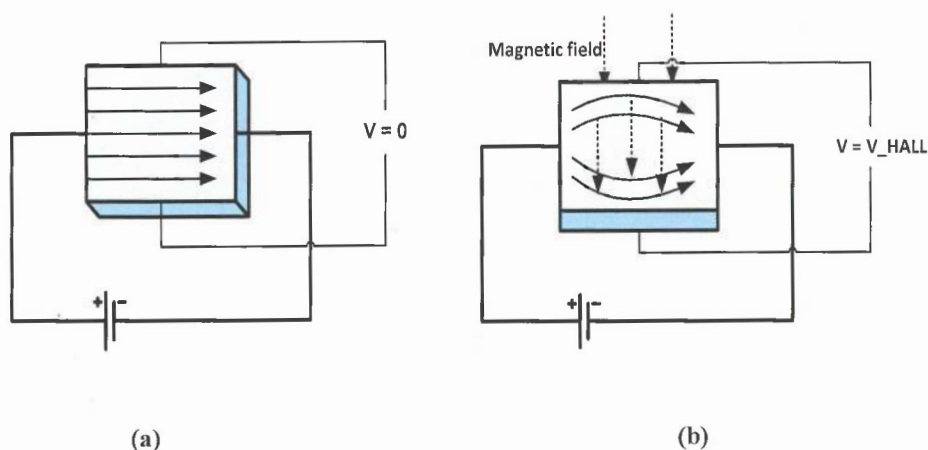


Figure 4-8. The Hall Effect in a conductive plate, (a) without applying magnetic field, (b) applying magnetic field

Figure 4-9 shows a typical voltage biased Hall Effect current sensor. The Hall voltage is a low level signal typically of about 30 microvolt in a magnetic field of one gauss. This low magnitude signal requires a low noise, high impedance and moderate gain

amplifier. Because DC currents can flow in either direction, the amplifier output can be driven either positively or negatively. If power supply gives single 5V then the signal output range will be limited between 0V and 5V. The maximum and minimum limits between which the output signal can vary are known as saturation points. Negative saturation is specified relating to ground, while positive saturation is specified as how close the output can go to the positive supply rail [47]. These conditions are illustrated in Figure 4-10.

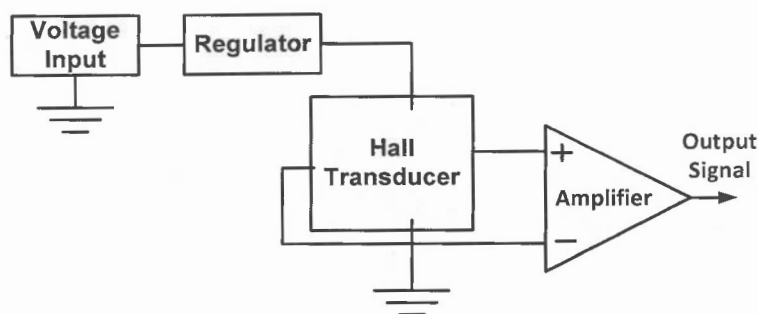


Figure 4-9. A typical voltage mode Hall Effect current sensor

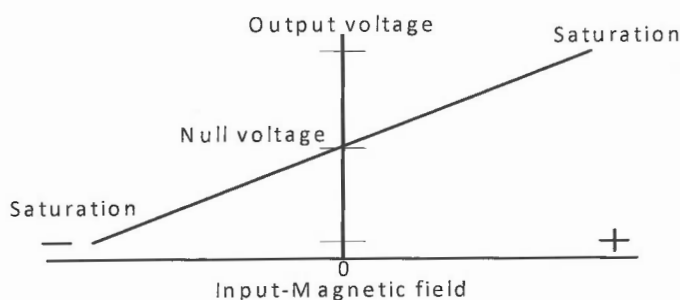


Figure 4-10. Hall Effect sensor transfer curve

In order to sense the current between the battery and the load, numerous AMP25 Linear-to-60A hall sensors from Amploc were used. Amploc current sensors provide galvanic isolation and are capable to measure DC, AC and complex waveforms. Their operation temperatures range from -55°C to $+125^{\circ}\text{C}$. They are light weight, water resistant and the terminals are gold plates (supply voltage, ground and output signal) [48], as shown in Figure 4-11. All sensors' electrical characteristics are listed in Table 4-3.

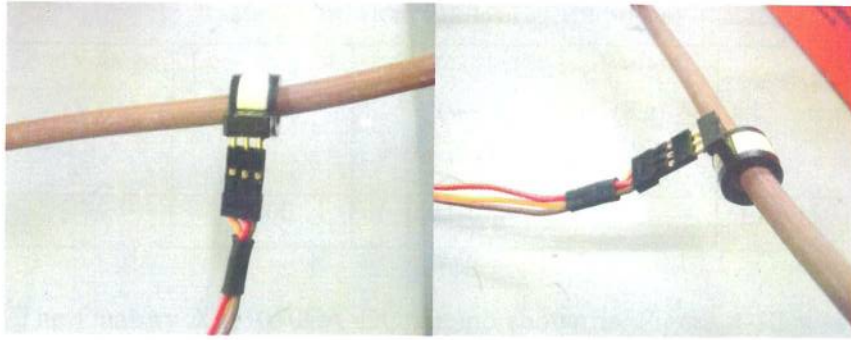


Figure 4-11. AMP25 linear-to-60A current sensor

Table 4-3. Electrical characteristics of AMP25 linear current

Supply voltage, V_s	+4.5 to +10VDC
Supply current	10 mA max
Output current	2 mA max
Offset voltage, V_o (sensed $I = 0A$)	$V_s / 2 \pm 2\%$
Output voltage, V_o is proportional to V_s	
Temperature error Null or gain	0.3%/ $^{\circ}C$
Response time	3 μ Sec
Linearity (Full scale)	1 %
Accuracy (Full scale)	$\pm 2\%$
A.C. Hysteresis error	0.5 %

4.5 Electrical load and engine description

Electronic load: The Zentro-Elektrik type ELA1500/75/100D electronic load for DC voltages was used as the load. This has three selectable modes of operation: constant current mode, constant resistance mode and constant power mode. An IEEE488.2/RS232/USB interface Integrated with Lab-View driver for external programming. The current, power or resistance of the load were programmed using an external control voltage where a change in voltage from 0V to 10V changed the set value from 0% to 100%. The load's specifications are in Table 4-4.

Table 4-4. DC electronic load specifications

Power (W)	Load voltage (V)	Load current (A)	Load resistance (w)	Weight (Kg)	Model number
1500	1-75	1-100	0.02-10k	12	ELA1500/75/100D

Engine: The Dualsky XM5050CA DC engine shown in Figure 4-12 was selected. Maximum engine power required 1290 Watts at 47.4A to generate the maximum RPM of 5460.



Figure 4-12. Dualsky XM5050CA DC engine

4.6 Data acquisition system

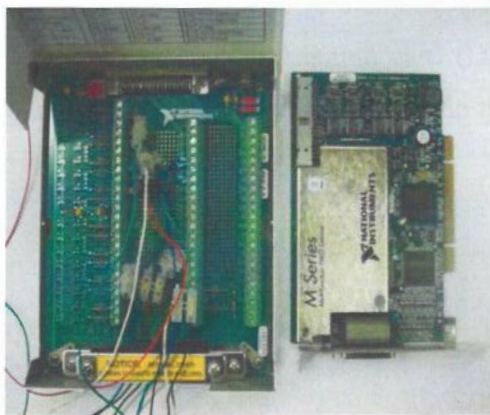
The data acquisition system (DAQ) manufactured by National Instruments, high speed PCI-6259 with M-Series multifunction board, via the Data Acquisition Toolbox the PCI-6259 can be supported in Simulink and used to send and receive data between the hardware and MATLAB. See Table 4-5 for specifications of the DAQ card.

External connections were made using the National Instruments SCB-68 connector block and plug in data acquisition device card using 68-pin connector, see Figure 4-13 (a). The SCB-68 provides a robust and very low noise signal termination and is compatible with other National Instruments single and dual-connectors [49]. Single core wire was deemed adequate for connections between the rack and the sensors. The sampling time rate was 3.3Hz.

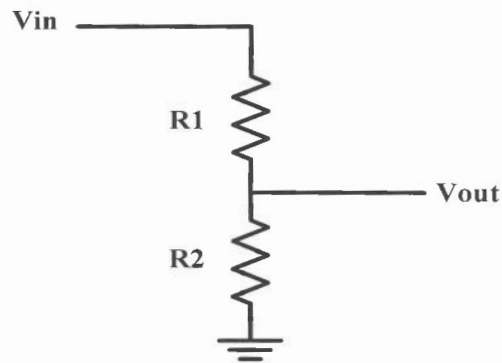
However, the SCB-68 rack can accept only voltage levels below 10V, so a step down voltage divider was used for voltages above 10V, these included the FC voltage,

battery voltage and bus voltage. The software was then used to scale the readings back. Figure 4-13 (b) shows the voltage divider circuit, it referenced to ground is formed by connecting two resistors R_1 and R_2 in series ($R_1 = 100\text{K}\Omega$ and $R_2 = 27\text{K}\Omega$). By applying Ohm's law: $V_{in} = I * (R_1 + R_2)$, $V_{out} = I * R_2$ and $I = \frac{V_{in}}{R_1 + R_2}$, so the output voltage can be found by using following equation:

$$V_{out} = \frac{R_2}{R_1 + R_2} * V_{in} \quad (4.1)$$



(a)



(b)

Figure 4-13. (a) DAQ card in the right side of the picture and NI SCB-68 connector block in the left side of picture, (b) Voltage divider circuit

Table 4-5. NI-6259 DAQ card's specifications

Family	Bus	Analog Inputs	AI Resolution (bits)	Analog Outputs	AO Resolution	Max Update Rate (MS/s)	AO Range (V)	Digital I/O	Correlated (clocked) DIO
NI 6259	PCI	32	16	4	16	2.8	$\pm 10 \pm 5$	48	32, up to 10 MHz

4.7 Chapter summary

A description of the various components used in the experimental set-up was described in this chapter alone with a brief overview of their functions and specifications. In addition to that safety consideration had to be taken into account. The Nexa FC system had to be installed in well-ventilated lab area equipped with hydrogen alarm sensors, extractor fan for air circulation in the lab. Furthermore, the Nexa power module has automatic provision to ensure operator safety and prevent equipment damage. To test the FC dynamic response and performance, an ON/OFF switch was installed between the battery side and the main circuit of the hybrid system. The switch used to connect/disconnect the batteries for charging/discharging. Moreover, the data acquisition card (DAQ) used to log the hardware data was also covered. All experimental data used in the analysis in following chapters were logged using this DAQ card.

5 Initial Experimental Results of Model Validation and System Performance Characteristics

In this chapter the dynamic performance and transient response of Nexa fuel cell system under various load conditions will be covered. The dynamic performance tests were separated into four stages: start-up, step-up load, irregular load variation and shut-down. Moreover, the sealed lead acid battery model used in the simulation will also be validated.

5.1 PEM fuel cell model validation

The PEMFC model is semi-empirical model, derived from theoretical considerations and experimental results. Experimental data was obtained from a Nexa FC, which have been using as inputs to simulation model. The model details were described in Chapter 3. The comparisons between the outputs stack voltage and power during start-up and step-up load variation from the experimental and simulation results show good agreement. In the initial phase of the start-up sequence, there is a difference in the voltage outputs, this due to the difficulty of accurately modelling the initial conditions during the start-up. However the response has a similar pattern and follows then-on the same behaviour. The stack voltage declines from 37V to 31V while the power out increases from 330W to 938W as shown in Figures 5-1 and 5-2 respectively. It can be seen from this comparison that the PEMFC dynamic model works well.

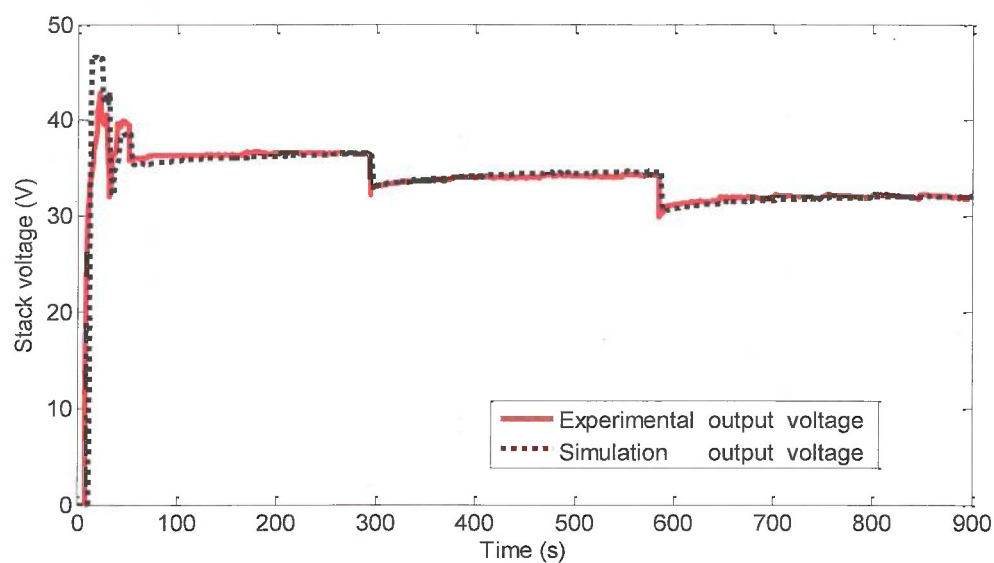


Figure 5-1. Comparison of experimental and simulation output stack voltage

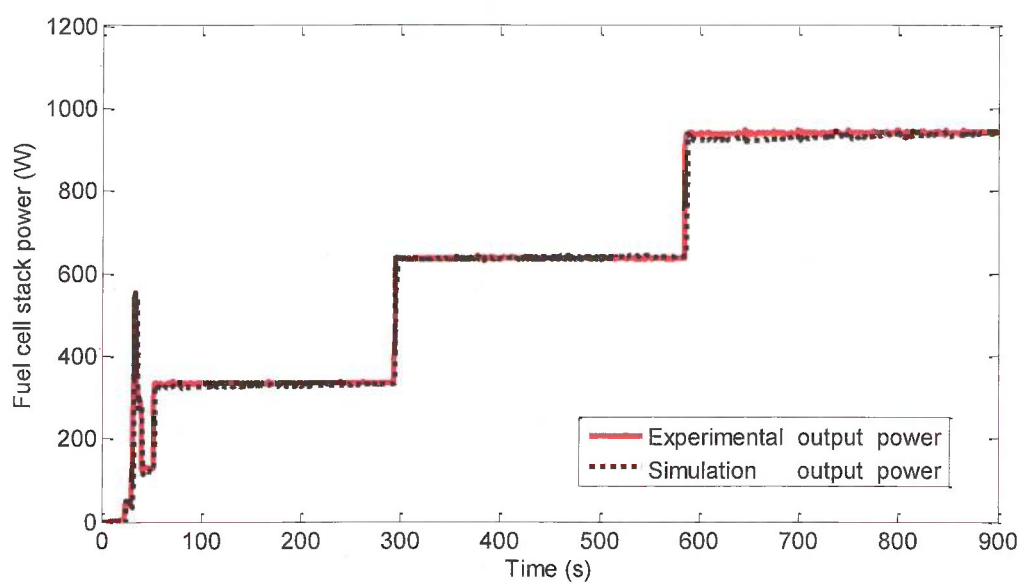


Figure 5-2. Comparison of experimental and simulation output stack power

5.2 Sealed lead acid 12V battery model validation

An experimental test was conducted to validate a battery block model in SimPowerSystems® toolbox, which represents the most popular types of rechargeable batteries. The specification of the WP18-12 sealed lead acid battery was programmed into the block. The experimental setup consisted of WP18-12V sealed lead acid battery, current and voltage sensors, EL 1500 electronic resistor load and computer to recorder data. The battery was connected to EL 1500 electronic load, which drew 10A for almost one hour. Initially the battery's voltage was 12.7V and this dropped gradually to 9.9V after 58 minutes, at this voltage level the battery became discharged. The plots of battery discharge voltage vs. time for both experimental and simulation results are shown in Figure 5-3. Very good agreement can again be observed.

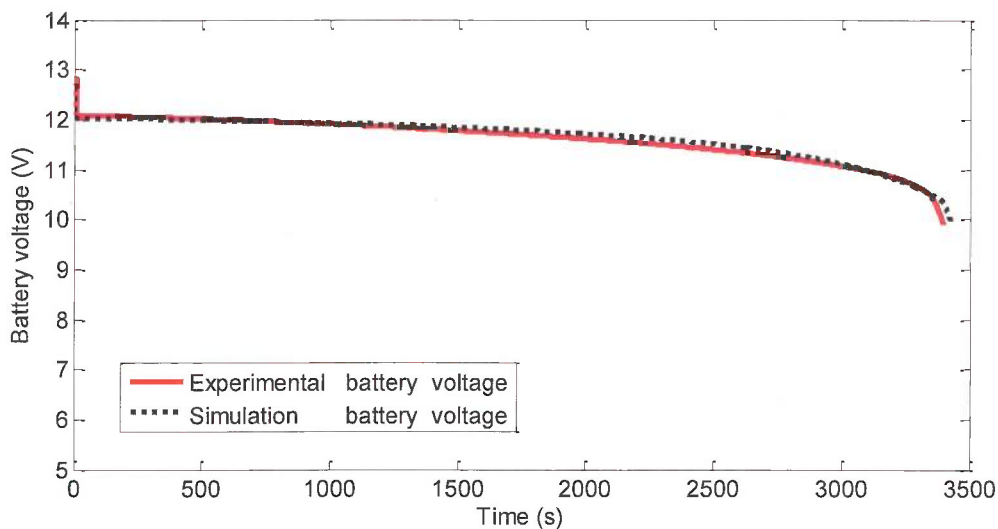


Figure 5-3. Comparison of experimental and simulation battery voltage

5.3 Polarization characteristics of Nexa PEM fuel cell

According to the manufacturer manual [45] Nexa's net output power ranges from zero at system idle to 1.2 kW maximum, and net output current ranges from zero to 46A across the operating range of the power plant. Output voltage varies with operating load according to the polarization characteristic of the FC stack. Normal idle voltages of the Nexa system are approximately 43V DC at no load to 26V DC at full load. In Figure 5-4 shows the relationship between the cell voltage and the current density. The characteristic shape of the curve shows three irreversibility voltage loss regions of Nexa PEMFC.

First is the activation drop region: in this region the voltage drops rapidly from the normal idle voltage because of the slow starting up of the chemical reaction, which takes place at the surface of the electrodes [8]. The voltage losses are due to the work required to drive the chemical reaction which transfers the electrons to or from electrodes.

Secondly, Ohmic drop region: in this region the voltage drop curve is almost linear, see Figure 5-4. This is due to electronic and ionic internal resistances of the electrodes and electrolyte, respectively.

The final region is the mass transport drop region. The voltage would be expected to drop rapidly immediately after the Ohmic drop region due to the limitation in the concentration of the reactants (oxygen and fuel). There is no possibility of recording that because the Nexa power module has an automatic provision to ensure operator safety and prevent equipment damage, driving the system to shutdown before the data in the mass transport region can be recorded.

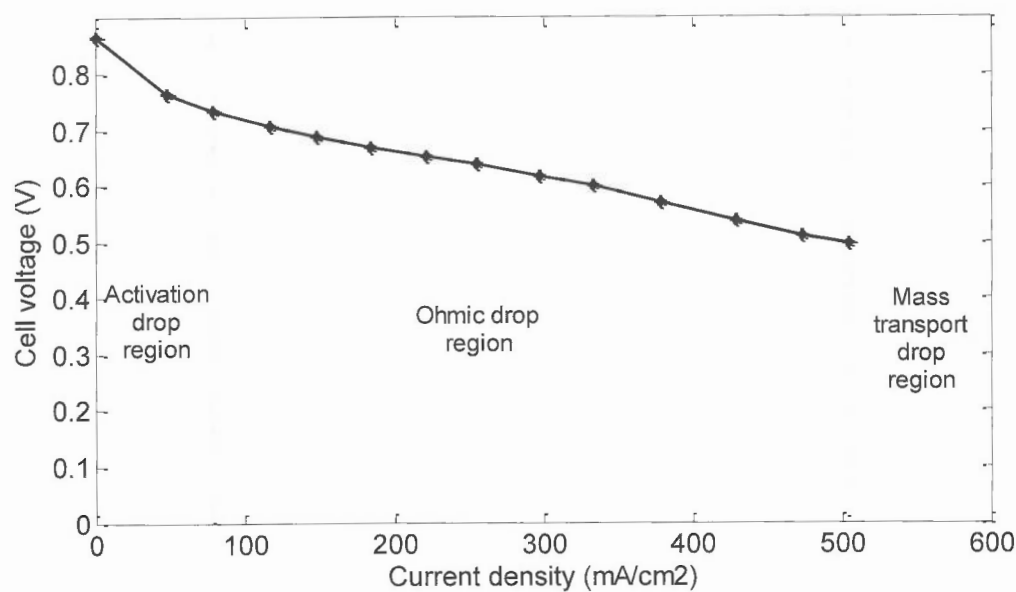


Figure 5-4. Polarization curve of Nexa FC

5.4 Nexa PEM fuel cell transient response during the start-up sequence

During the start-up and shut down sequences, the 1.2kW Nexa power module FC must be connected to the 24V batteries and provided with an adequate hydrogen fuel supply. The transient response of transmitted Nexa FC status, current and voltage during the 35 seconds of the start-up stage are shown in Figures 5-5 and 5-6. When the system is switched on, it remains in the OFF state then the starting-up sequence began with the 24V battery supplying power to the control board. The system changes to the stand-by state after about 2 seconds. In this state, sensors and actuators are activated and the onboard microprocessor begins to continuously send system data and status signals. Thereafter at 13 seconds, a 5V 'start' signal initiates the start-up sequence. The hydrogen solenoid valve open's to enable hydrogen to flow to the FC stack and the air pump is turned on, providing air to the stack. Finally at the end of 13 seconds, the cooling fan is turned on for regulating temperature and dilution of purged hydrogen.

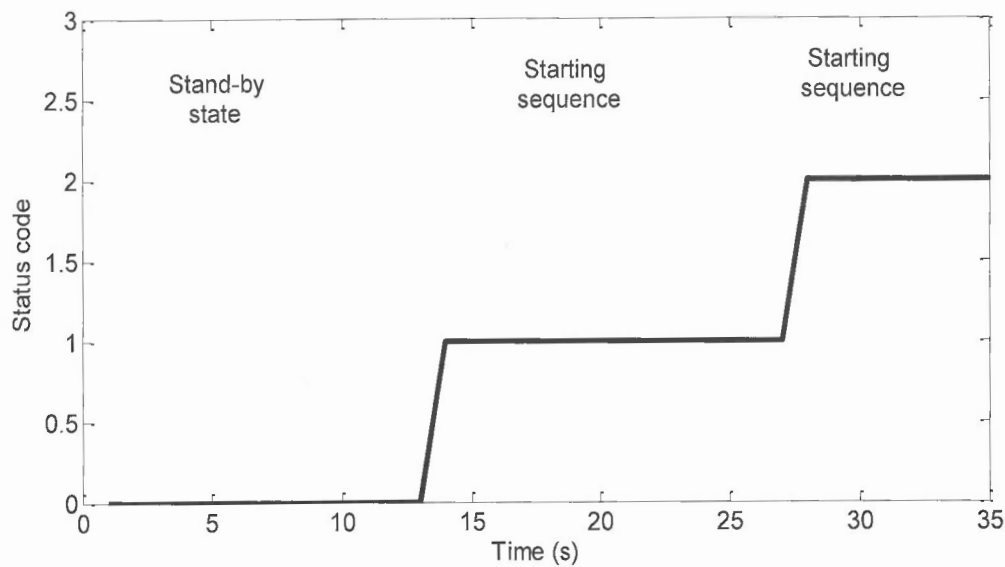


Figure 5-5. Nexa power module transmitted status during start-up stage

From Figure 5-6, it can be seen that after 15 seconds the stack voltage begins to show a slight and the voltage rise's to 46.41V. It is worth noting that at this stage, no output current was delivered to the external load. At 21 seconds the current gradually increases from zero to 1.2A and the corresponding voltage decrease to about 42V. Finally, At 28 seconds when normal operation status is reached, the Nexa module control board internally transfers parasitic load from the external battery to the FC stack and an external load relay control signal is sent to connect the FC to the external load. As can be seen from Figure 5-6 this results in a rapid increase in stack current with an overshoot due to fast demand from the air pump, while stack voltage decreases accordingly.

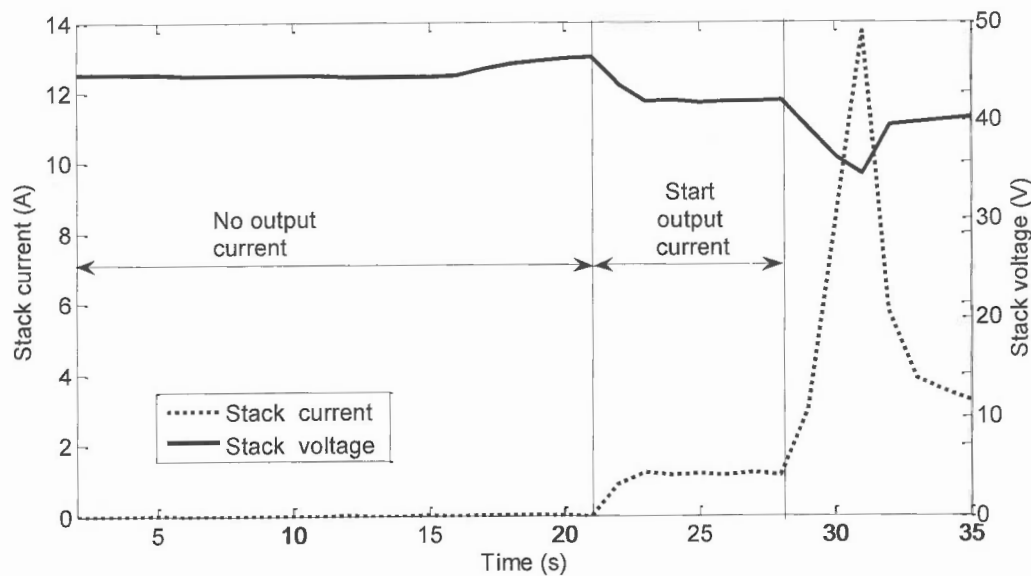


Figure 5-6. Transient responses of the stack output current and voltage during start-up stage

Following the stand-by sequence, the air pump and cooling fan voltages jump from 0 to 43% and 50%, respectively as shown in Figure 5-7. The air flow rate fluctuates around 20 slpm, its response has an overshoot at the beginning of the start-up and then during normal operations when all the auxiliary components loads are connected to the FC as shown in Figure 5-8. When the external load was connected to the FC at 28 seconds, the voltage of the air pump increased with an overshoot in order to supply sufficient oxidant (air) and flush the stack of residual water. The flow rate of air rises proportionally to satisfy the FC consumption. However, the cooling fan voltage drops to 35% so as to regulate the FC stack temperature. In reality, as shown in Figure 5-9 the stack temperature does not change significantly during the start-up sequence, the cooling fan voltage is kept constant at 35%.

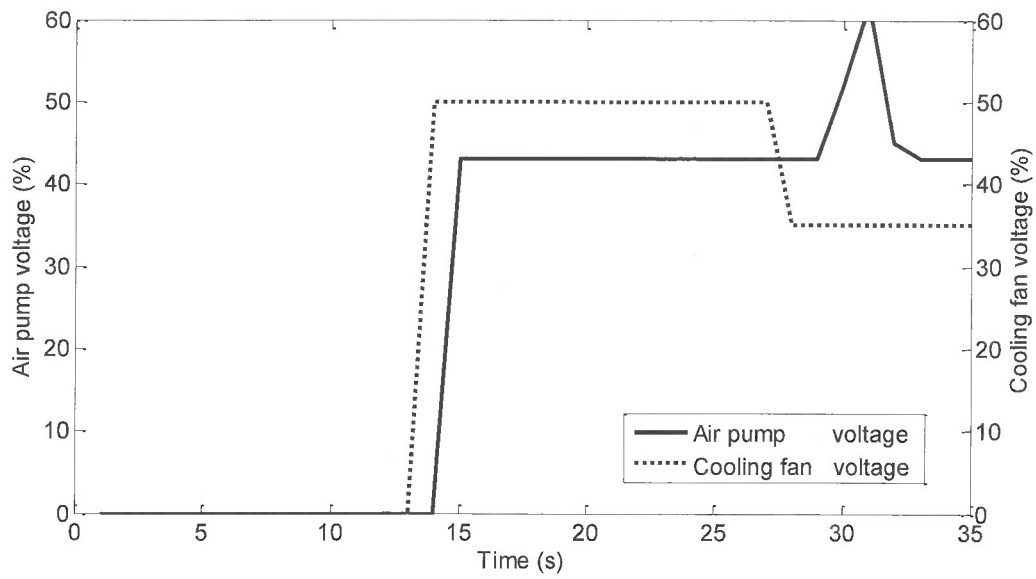


Figure 5-7. The air pump and cooling fan voltage during start-up stage

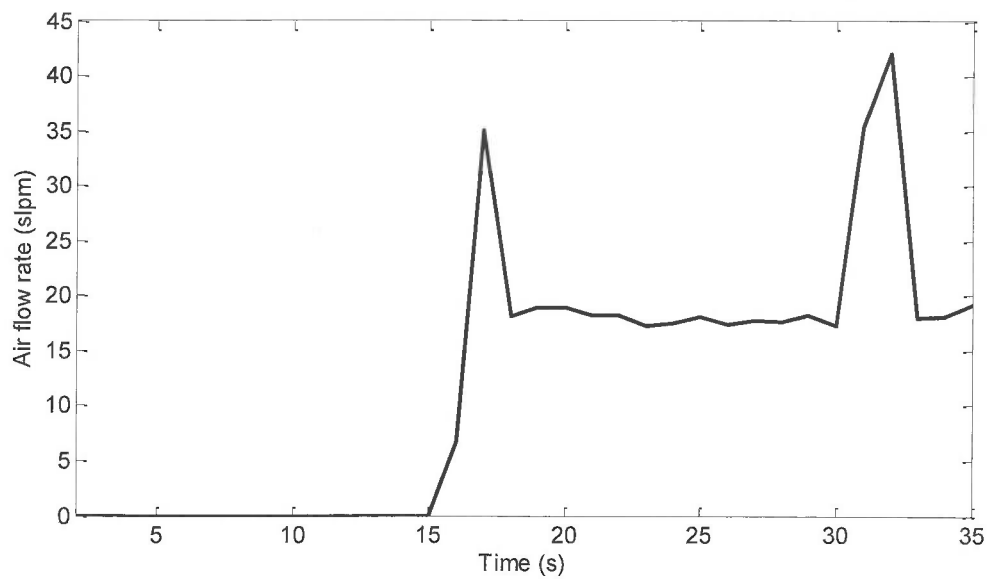


Figure 5-8. Air flow rate during start-up stage (slpm)

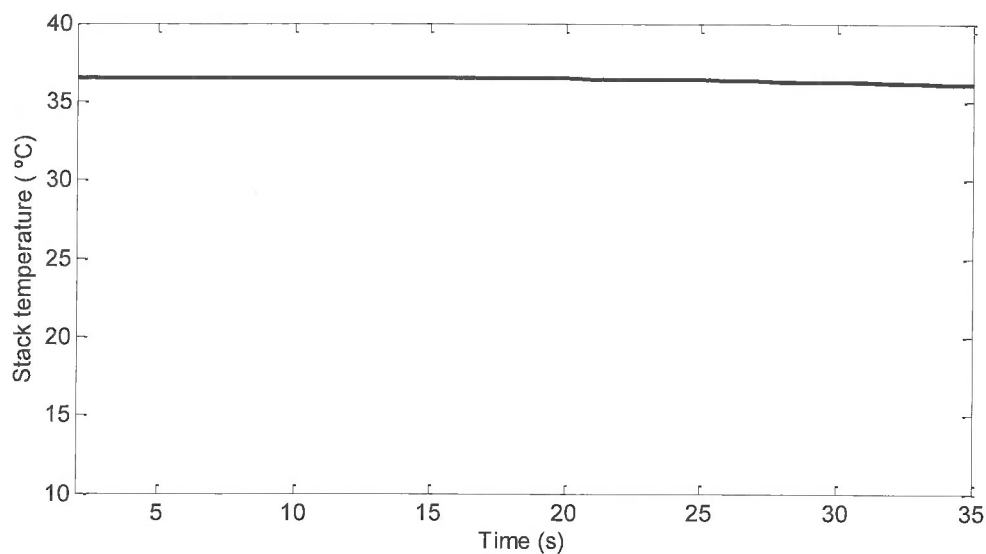


Figure 5-9. Stack temperature during start-up stage

5.5 Nexa PEM fuel cell transient response during the step-up load variation

This test examined the transient responses of the FC parameters (stack current, stack voltage, air pump voltage....etc.) for a stepped increase in load at 293 seconds, 585 seconds and 919 seconds, see Figure 5-10. Over the period of the test the stack current increased in steps from 10A to 20A, to 30A and finally to 40A in step of 10A each time. The corresponding stack voltages were about 37V, 34V, 32V and 30V, respectively. The maximum power of 1.2kW was achieved after 919 seconds when the stack current was stable at 40A and the stack voltage at 30V. As the current increased so did the frequency of purge valve operations in order to prevent water flooding of the anode channel and the anode gas diffusion layer. The interval between purge valve opening and closing was about once every 96 seconds in the low-current region of around 10A, and increased to once every 30 seconds in the high-current region at 40A. Figures 5-11 and 5-12 show the observed purging effect on stack voltage.

The red circle area in Figure 5-10 shows the small transient stack voltage undershoot and stack current overshoot that occurred when the current increased from 20A to 30A. The small observed overshoot in the current occurs for three possible reasons:

First, the different operating conditions leads to disparate water saturation level particularly after a long course of running. Secondly, both the humidified water and product water alter the membrane wettability [40]. Third possibility, it is due to an inrush current of the load when the step change is applied. The voltage undershoot because of an unexpected load action causes temporary dehydration due to electro-osmotic drag on the anode side, and air feed starvation on the cathode side. The membrane resistance jumps and inevitably leads to a sharp drop of cell voltage [43].

Figure 5-11 is a more detailed plot of the FC stack voltage for the period between 650 and 900 seconds when the current was more or less constant at around 30A and the FC stack ran without any load variation. It can be seen that the stack voltage actually experiences periodic drop every 50 seconds then the purge valve operate to remove water from the anode channel. During normal FC operation, liquid water condenses and accumulates because of the dead-end configuration of the FC anode side. Prior to the purge valve opening, the stack voltage experiences a slight decline from 32.2V to approximately 31.76V due to water flooding. An immediate performance enhancement after the purge valve open can be seen as the voltage increase. The purge valve status values are '1' when the valve is open and '0' when the valve is closed as shown in Figure 5-12.

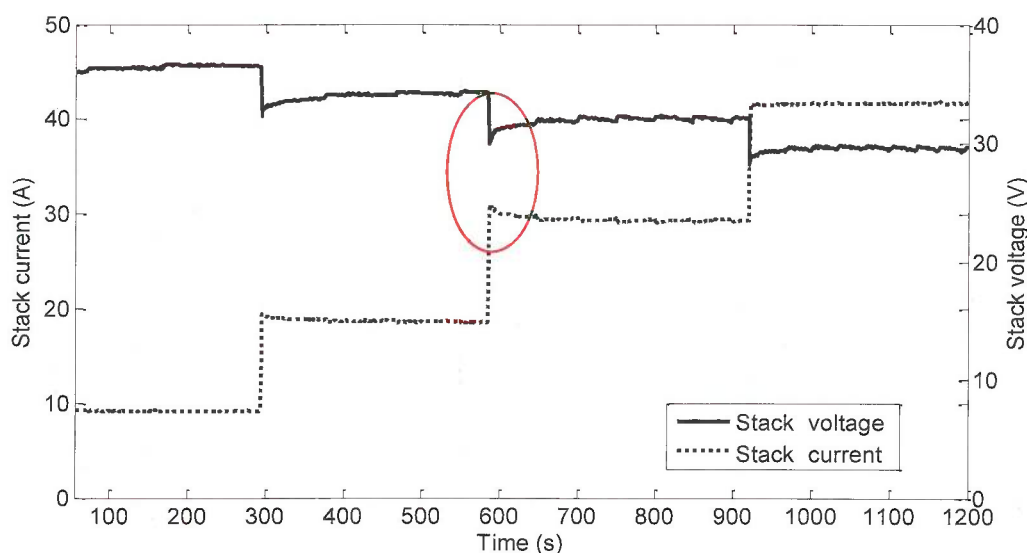


Figure 5-10. Transient responses of the stack current and voltage during step-up stages

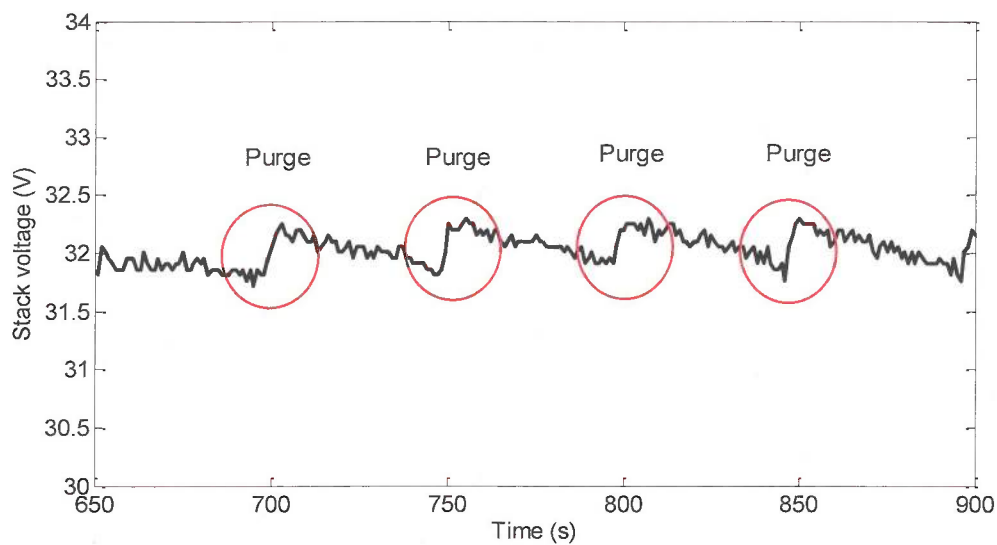


Figure 5-11. Effect of purge valve operation on the stack voltage during constant load

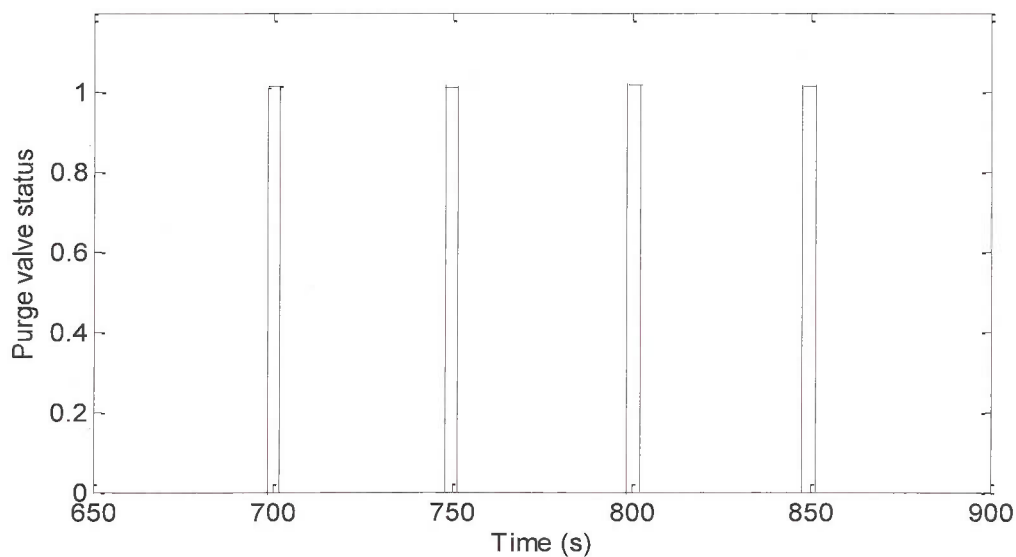


Figure 5-12. Purge valve status during constant load (0 = valve closed, 1 = valve open)

The stack temperature increases as long as the stack current increases as illustrated in Figure 5-13. Figure 5-14 shows the air pump voltage following the same step pattern as the stack current. The cooling fan voltage on the other hand is constant at 35%, up to about 700 seconds, after that it increases to about 42% in a series of seven relatively small steps.

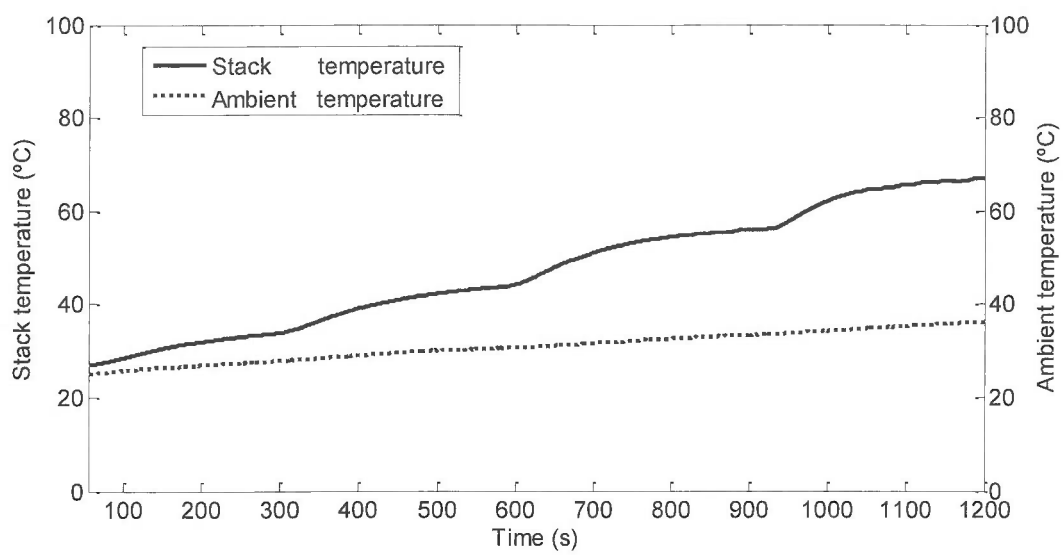


Figure 5-13. Stack and ambient temperatures during step-up stages

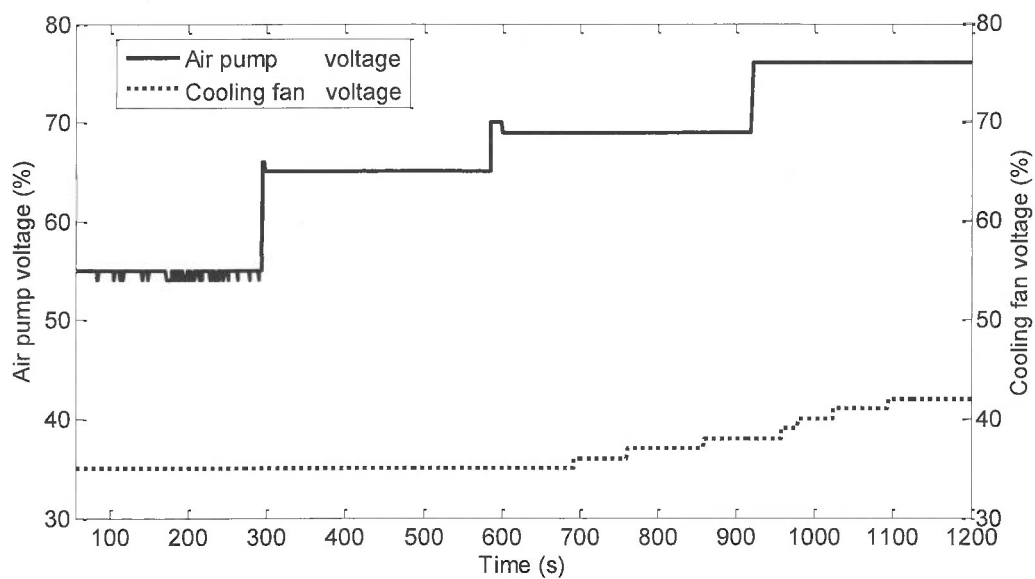


Figure 5-14. The air pump and cooling fan voltages during step-up stages

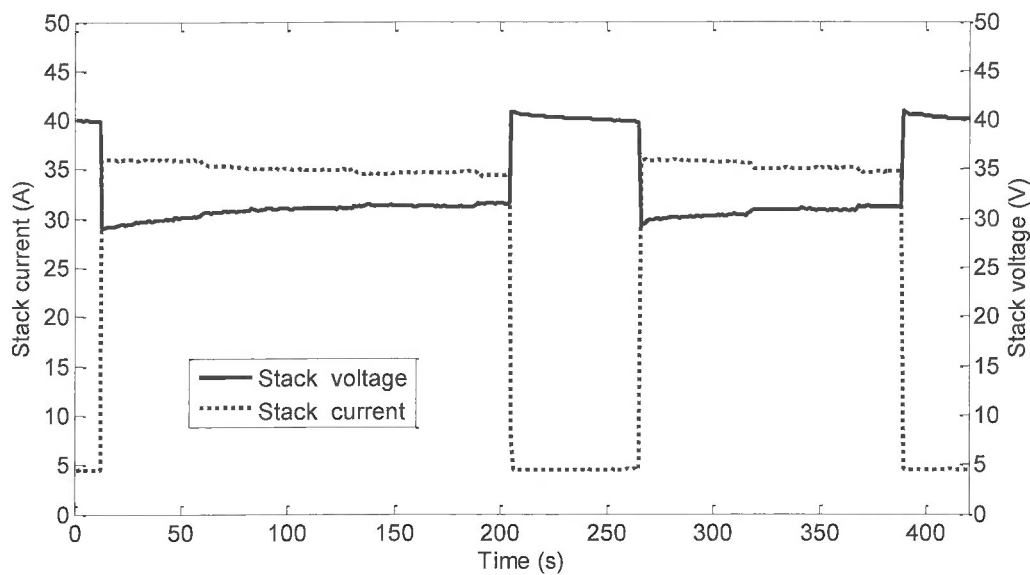


Figure 5-15. Transient responses of the stack current and voltage during highest FC step-up

Figure 5-15 shows the highest transient responses of the Nexa FC for step-up in the load current. The load current increased at 12 seconds and 265 seconds in one jump from about 5A to 35A. Over the period of the test the stack current took one second to increase in steps from 5A to 35.99A and from 5A to 35.9A following the load, respectively. The stack voltage dropped from 40V to 29V and from 39.9V to 29.29V with small undershoots and took about 50 seconds to return operating at constant voltage (approximately at 31V). If we increase the load current increase from about 5A to just over 35A in one step, then the Nexa FC will shut-down.

5.6 Nexa PEM fuel cell transient response under irregular load variation

The main objectives of this test were to study effects of temperature and air flow rate supplied by the air pump on the dynamic performance of FC stack. In the test the FC stack supply power to irregular load variation over a period of 1600 seconds. The experimental results are presented in Figures 5-16, 5-17 and 5-18. The temperature commonly increases during FC operation due to exothermic reaction heat transfer and internal heat dissipation. PEMFC stack temperature changes continuously with the load current. However, the temperature also directly affects the rate of chemical reactions and the transport of water and reactants. High temperature might impose thermal stress on the membrane and cathode catalyst and cause degradation. On the

other hand excessive supply of coolant lowers the temperature in the stack and will reduce the rate of the chemical reactions and water activity. Consequently overall efficiency of the system drops as parasitic power increases [24]. So operation under too-low or too-high temperature is not recommended except for extreme circumstance such as subzero application, where it can be regulated by proper thermal control [50]. The stack temperature response follows the load changes in a similar way to current increase or decrease but change slowly without any overshoot or undershoot as shown in Figure 5-17.

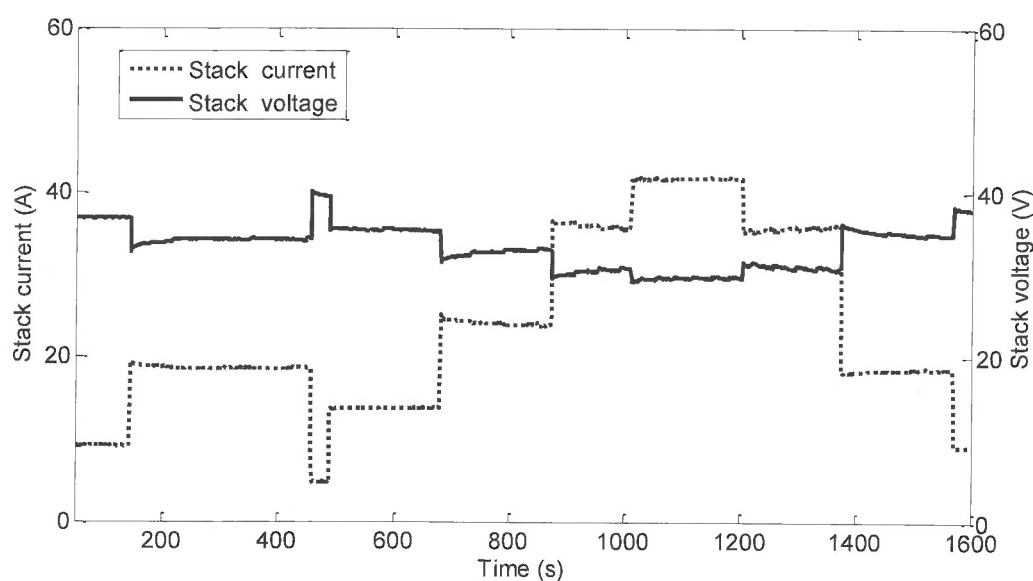


Figure 5-16. Transient responses of the stack current and voltage during irregular load variation

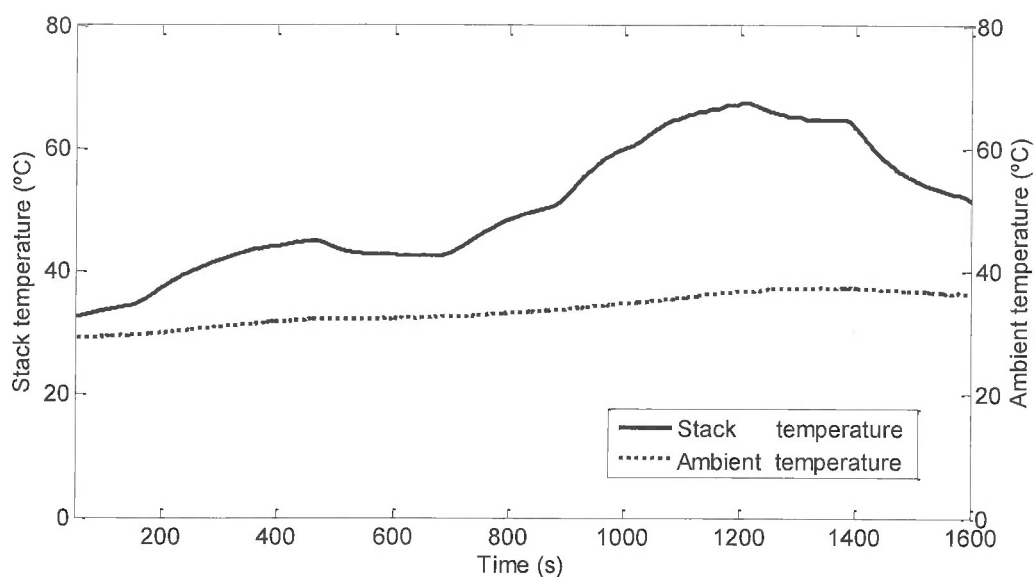


Figure 5-17. Stack and ambient temperatures during irregular load variation

Figure 5-18 presents the Nexa FC air pump and cooling fan voltages, it can be seen that the air pump flow rate directly follows the current fluctuation with minimum delay. However, the decreasing amount of air flow rate results in oxygen depletion at the FC cathode channel during power generation. The Nexa FC operation shows that the air flow does not significantly affect the FC stack dynamic performance.

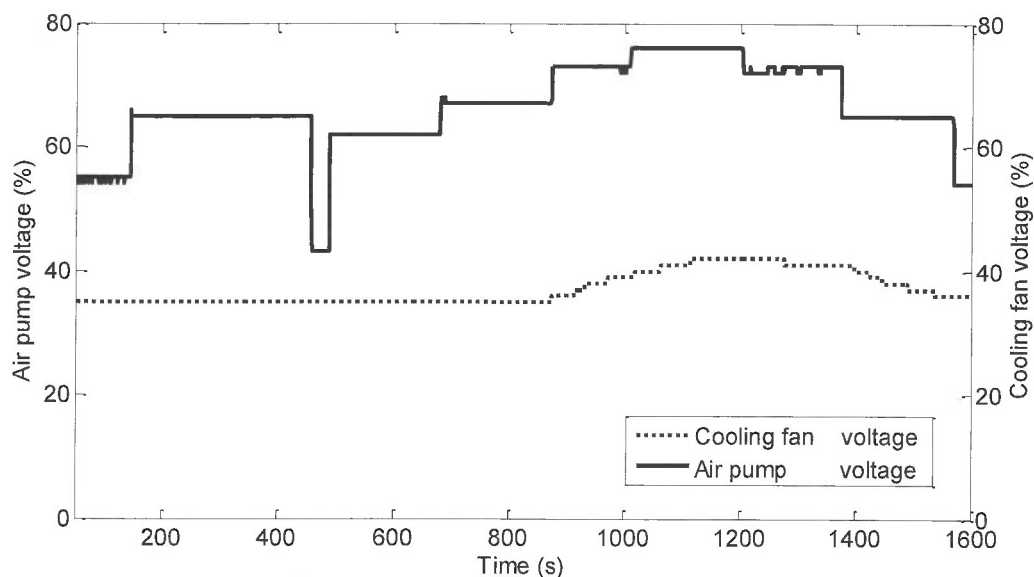


Figure 5-18. The air pump and cooling fan voltage during irregular load variation

5.7 Nexa PEM fuel cell transient response during the shut-down sequence

In shut-down mode, the 5V start signal removed from the FC stack and the external load relay was open to isolate the FC stack from the external load. Since the FC sufficiently operated for longer than 5 minutes, therefore the shut-down sequence continued to remove residual water products from the cathode and anode flow channels using the air pump and hydrogen purge valve.

The transient responses during the shut-down stages are shown in Figures 5-19, 5-20, 5-21 and 5-22. The shut-down begin at 419 seconds, the current drops to 1.58A within 1 second, while the stack voltage increases to 42V. At 438 seconds, the control board internally transferred the parasitic load from the FC stack back to the external battery, which causes the small undershoot in the current, mirrored by small overshoot in the voltage. At 447 seconds, the current drops almost to zero while the stack voltage increase gradually until reaches the OCV value of 46V in idle state, the air pump and hydrogen purge valve continues to remove residual water products from the anode and cathode flow channels as shown in Figures 5-19, 5-20 and 5-21. Figure 5-20 shows how the air flow rate increases from 20 slpm to 59 slpm in the period from 438 to 483 seconds and then drops to zero. At 452 seconds, the voltage of the cooling fan falls from 35 % to zero, later on at 482 seconds, the air pump drops sharply to zero as shown in Figure 5-21. Upon entering shut-down sequence, the stack temperature begins to decline and drops quite gently as shown in Figure 5-22.

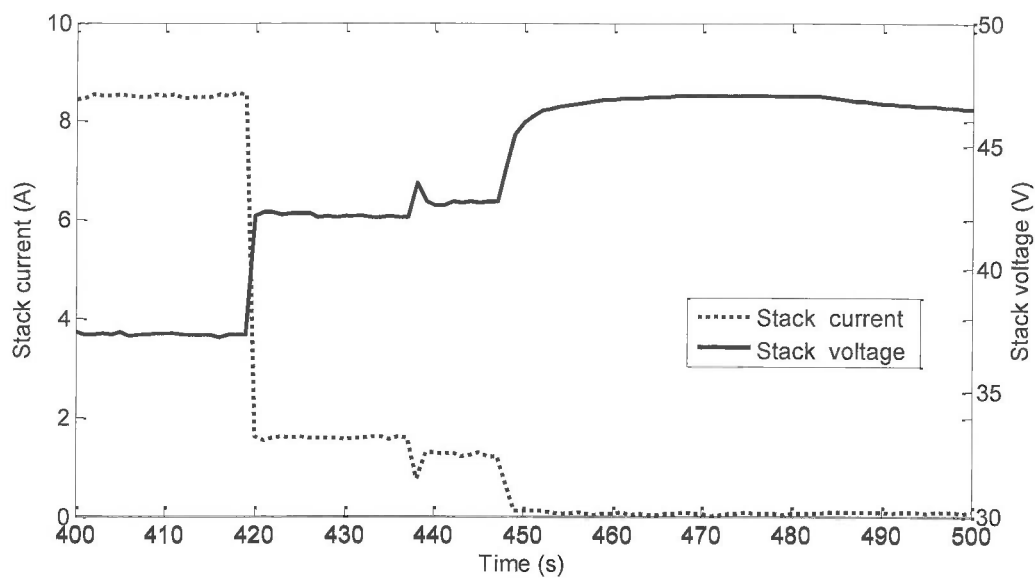


Figure 5-19. Nexa PEMFC transient responses of the stack current and voltage during shut-down stage

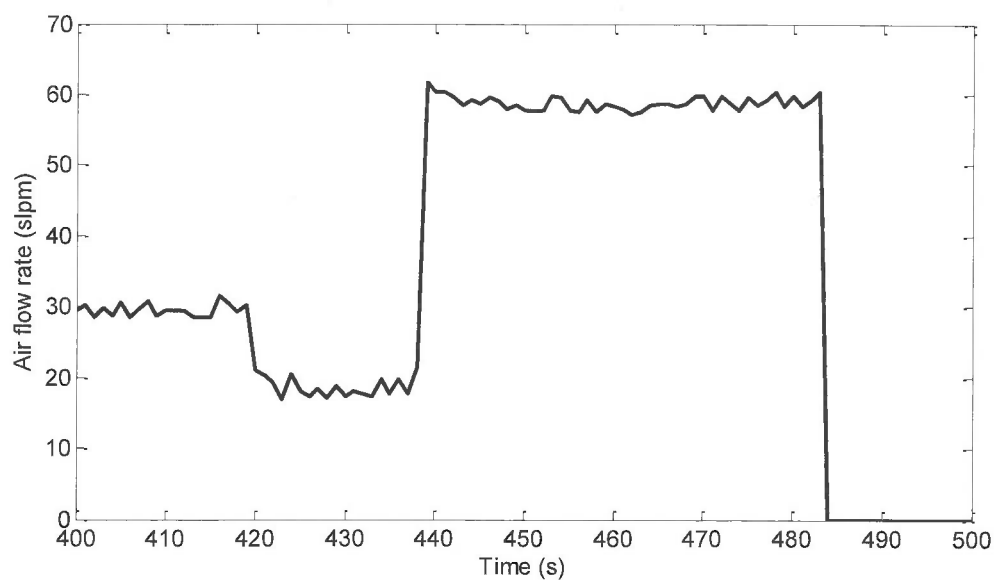


Figure 5-20. Air flow rate during shut-down stage (slpm)

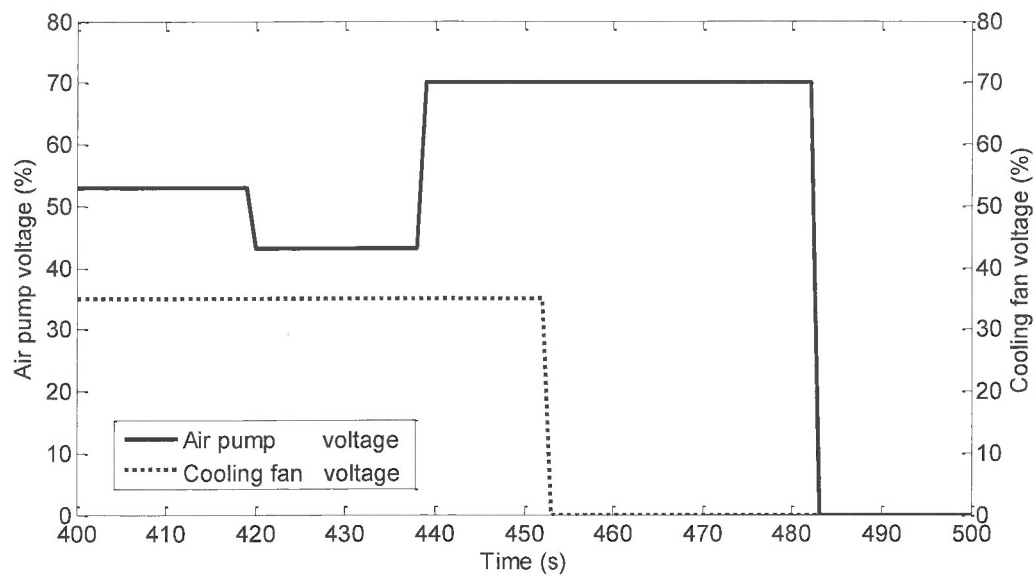


Figure 5-21. The air pump and cooling fan voltages during shut-down stage

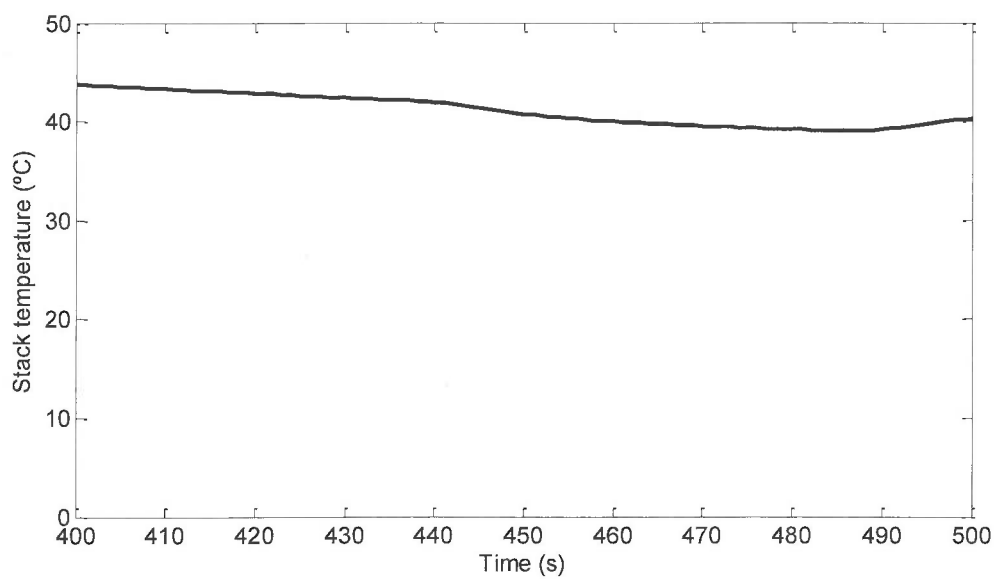


Figure 5-22. Stack temperature during shut-down stage

5.8 Voltage and current ripples

The Hall Effect current sensors are used to measure the current supplied to the load and the current supplied to or from the batteries. Significant ripples in the current measurement were observed in the recorded data from the sensors. Figure 5-23 shows the load and battery current waveforms when zooming-in on the ripples that were recorded using an oscilloscope. The ripples are caused mainly by switching of the internal metal oxide semiconductor field effect transistors (MOSFETs) in the DC/DC converters which produce high noise levels and EMI which disturbs or limits effective performance of electronic and electrical equipment. All of that are picked up by the Hall Effect current sensors.

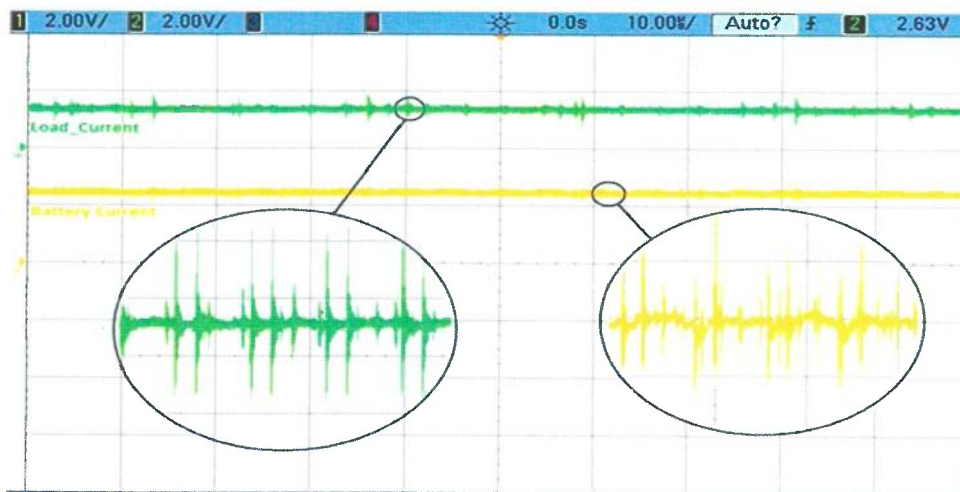


Figure 5-23. Load and battery current waveforms 5A/Division

Ringling in the parasitic capacitance and inductance in the system caused spikes during every switching event. Another source for the ripple is non zero ground potential reference. Ideally it is assumed that each device in the system has the same or zero ground reference potential. In practice, due to the internal resistance of the cables and wires, some devices operate at a different ground potential reference. This will cause unwanted signals or noise generated from the DC/DC converters to disturb the ground potential reference of the Hall Effect sensors, which will then reflect on its reading and introduce variations and ripples in the readings. Therefore, a low-pass filter was used to filter out the noise and voltage perturbation from the measurement data.

5.9 Dynamic response of the engine and load

This experimental test was to examine the dynamic response of the electrical engine, and compare it with the dynamics of the electronic load. During the test the Nexa FC hybrid system supplied power to the Dualsky XM5050CA DC electric engine under irregular throttle command inputs; and the current demand was recorded. Next the engine current demand load profile was implemented in the programmable Zentro-Elektrik type ELA1500/75/100D electronic load. Figure 5-24 shows the load current following the same pattern as the engine current. For instance, at 218 seconds the throttle jumps from low throttle to about 55% throttle resulting in the engine current to increase from 6.34A to 30A in two seconds, at the same time if we examine the load current, it performs in a very similar fashion, with load current drawing about 30.8A.

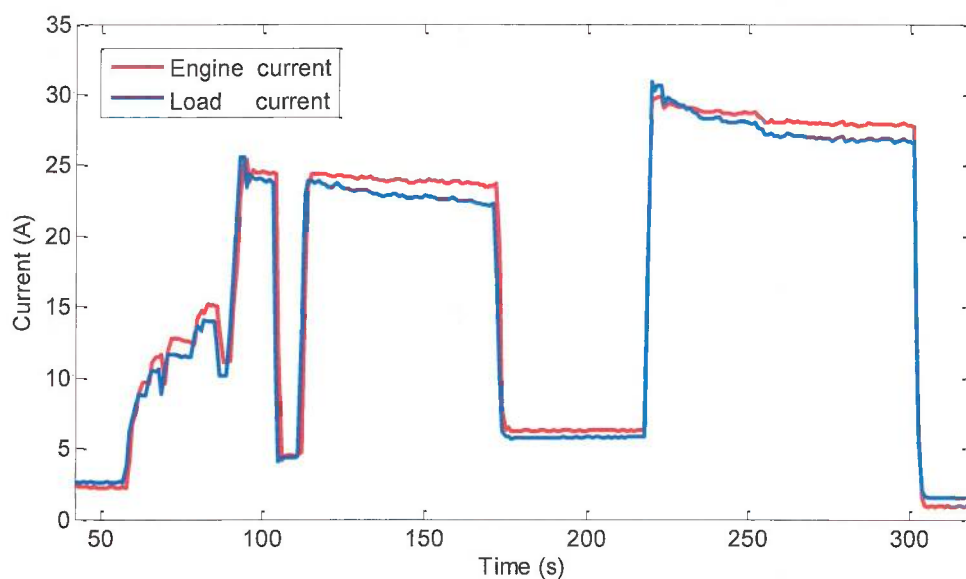


Figure 5-24. Load and engine current under irregular throttle demand

5.10 Chapter summary

The experimental and simulation results showed good agreement for FC and battery models validation. The dynamic performance tests were carried out and separated into different stages: start-up, step-up load, irregular load variation and shut-down. The highest transient response of the Nexa FC was observed during the step-up load current. During the test it was found that the stack current took about one second to increase from 5A to 35.9A in one step following the load. This is maximum jump the system could tolerate in one step, if the load current is increased from 5A to just over 35A in one step, then built-in safety system will kick-in and the Nexa FC will shut-down to prevent any damage to the system.

It was found that the ripples in the measurement data are caused mainly by switching of the internal MOSFETs in the DC/DC converters, which produce high noise levels and EMI that disturbs or limits effective performance of electronic and electrical equipment. A low-pass filter was used to filter out the noise and voltage perturbation from the measurement data. Finally, experimental tests were conducted to examine the dynamic response of the electrical engine and compare it with the dynamics of the electronic load. The two components showed the same dynamic response. Next chapter will introduce the modified hybrid propulsion system (i.e. with the additional components add to the original Nexa system, namely, bidirectional DC/DC converter and batteries).

6 Fuel Cell Hybrid System

Mechanical or electrical systems that can be powered by two (or more) energy sources are referred to as hybrid systems. Today the use of hybrid systems in automotive applications in an attempt to reduce environmental pollution and lower running costs by improving system efficiency is just one example. There are two common hybrid system configurations: if the two power sources are directly connected to the load as in Figure 6-1 (a) that is called a passive hybrid system. If a controller (invariably electronic) is used to match and manage the power flow from the two sources to the load then the system is known as an active hybrid system as in Figure 6-1 (b) [53].

The main disadvantage of the passive system is that the nominal voltages of the two sources, here FC and battery must be matched, the power is passively distributed between the sources depending on the characteristics of each source and the maximum current will be limited to that of the source with the lower current capacity. The alternative suggested by Gao and others [52] is that a DC/DC converter be positioned between the two power sources to increase the peak output power and also reduce the mass and size of the system [51].

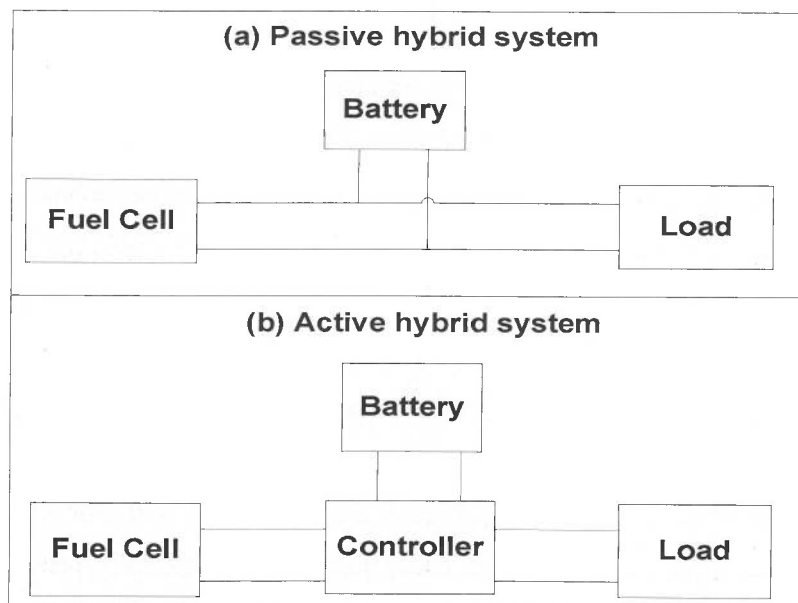


Figure 6-1. (a) Passive & (b) Active hybrid systems (FC and battery)

6.1 Review of fuel cell hybrid system control strategies

To achieve the power density of batteries with the energy density of FCs the two devices can be used together as a hybrid power source. Such a hybrid system could supply up to 100% of the power from the FC alone before having to draw power from the batteries. The problem of increased system mass and volume has been largely resolved through the use of commercially available power control circuits such as DC converters. Successful application of these has led to hybrid FC/battery power source with only a 13% increase in mass compared to the FC alone [53]. The batteries can be recharged by the FC subject to safety limits on both the FC power and battery charging current. Brodd has reported that lithium-ion cells and other rechargeable batteries because of their high energy output to weight ratio are already playing a significant role in limiting the weight of hybrid systems [54].

Lee et. al., tested the performance of a hybrid system consisting of FCs and a battery [55]. As expected they found that during low power demands the FC can charge the battery, which in turn assisted the FC to meet the energy demands at high loads and still maintaining high FC operating efficiency. They also made a number of more detailed observations one of which stated that as the humidification of the air supply increased, so did the FC stack power and that when there was a sudden increase in the load there was a short delay in the battery's response.

Jiang and Dougal compared the charging time of a battery using three active power sharing control strategies in a FC powered battery-charging station using both simulation and experiment [56]. The first baseline control strategy was simply equal rate charging. The other two more advanced strategies were pulse rate and proportional rate charging. The results showed that with the baseline strategy the total charging time was the longest. Using the proportional rate charging strategy, the total charging time was less than that of equal rate charging. However, the strategy that had the minimum total charging time was the pulse current charging strategy. Also it's worth mentioning that they found that total charging time was different depending on the initial state-of-charge of the battery; and that when using equal rate charging the battery that had highest initial state-of-charge became fully charged fastest.

Many strategies exist for the control of hybrid power sources. Jiang et. al., researched flexible strategies for multi-objective control of a power converter that could be applied to two different hybrid configurations of battery and FC without any change [57]. The simulation results showed that the multi-objective control strategy is able to select the regulation mode correctly. The FC current, battery current and battery voltage were regulated appropriately and validated using experiment results.

Kwi-Seong et. al., have investigated fuzzy logic control of FC/battery hybrid with the aim of improving system efficiency and battery life while maintaining acceptable load following capabilities [58]. The experimental results provided important information on the values to be assigned to parameters used in the equations of the simulation model. They also showed that fuzzy logic control could be used to maintain the battery state of charge at reasonable level and to optimize FC efficiency. Karunarathne et. al., developed a fuzzy logic control strategy for hybrid propulsion system consisting of a FC, battery, DC/DC converter, DC motor and propeller for an unmanned aircraft [59]. The fuzzy logic controller was used to monitor the state of charge of the battery, power demand, and then to identify the duty cycle mode for the DC/DC power converter which would buck/boost the FC/battery output voltage. This control strategy achieved significant energy saving when used for the propulsion system.

Thounthong et. al., developed a novel algorithm for maintaining a PEMFC as the main power source in a FC/battery hybrid system used in electric vehicles [60]. The major constraint on the control strategy is to avoid the rapid change of FC current to avoid problems of fuel starvation. They achieved this by controlling the rate of change of FC current and then reducing mechanical stresses such as fuel and water pressure in the tubes and stack of the FC system. Practical tests confirmed the excellent performances of the proposed control system. Super-capacitors (SCs) (or ultra-capacitors) are commonly used today to store electrical energy because they have a number of advantages particularly when used in applications that need high power instantaneously. Other advantages are the number of cycles in their life time, and the ability to hold a high charge. Payman et. al., have developed a new control strategy based on the flatness technique to control a hybrid system consisting of a FC as the main power source and a super-capacitor as the auxiliary source [61]. The strategy

regulates the DC bus capacitor energy and voltage to make the FC operates in a safe condition to deliver power and the super-capacitor functions during transient energy.

Electric hybrid systems use several power sources that have different constraints. Those constraints make the power management problem highly nonlinear [62]. Gavalletti et. al. used statistical learning theory to analyse and solve the energy management problem for FC powered electric vehicle. Theoretical approach was used to design the weight vectors of a neural network controller with the aim to reduce the fuel consumption for a given path. The numerical results showed that the strategy was good tool to solve such problems. Uzunoglu et. al., have produced a model of combined photovoltaic (PV)/FC/SC hybrid power generation with power flow controllers for stand-alone residential users [63]. The model allows design and analysis of any PV/FC/SC hybrid system for different power levels. The authors claim to have verified the model by accurately simulating a real system using the given system and control strategy for a complete day. Qigong et. al., have presented and verified a hierarchical predictive control strategy to simultaneously optimize the oxygen control and power distribution of a PEMFC/ultra-capacitor hybrid system [64]. The system has demonstrated that by transferring transient current demand from the PEMFC to the SC, it is capable of optimising the power management while protecting the PEMFC from oxygen starvation.

Wes and Ardalan carried out an experimental study to test how effective a two-degree-of-freedom control system could be in the power management of a Nexa FC/SC hybrid system [65]. Two DC/DC converters in voltage-control mode and current-control mode respectively, maintained a constant bus voltage and controlled the current drawn from the FC and SC. A rule-based algorithm and an optimization-based model predictive control algorithm were tested in real-time. It was found that the model predictive control algorithm could be more easily tuned when subject to a SC state of charge constraint in which the SC bank supplied power in periods of high demand and used as a buffer to sharp transients. They also found that under the conditions of this test the rule-based controller did not always utilize fully the power stored in the SC bank.

Majid et. al., considered the application of FC/supercapacitor/battery hybrid power source in electric vehicles and demonstrated a control technique which combined

fuzzy logic and flatness control to manage the power flow [66]. Flatness control was used to manage the energy flow between the FC which was the main power source and two auxiliary sources (SC/battery) which also acted as energy storages. Here the fuzzy logic technique was used to share the power flow between SC and battery, depending on the power demand and the relative state of charge of the SC and battery. Under the given test conditions the experimental results confirmed the control strategy. Fuzzy logic energy management strategy of a test bed hybrid electrical vehicle presented by Javier et al [67], the vehicle is equipped with a FC system, batteries and a super-capacitor. The control strategy considers the characteristics and constraints of each component of the hybrid system in the test bed. The results obtained showed good performance.

6.2 Fuel cell/battery hybrid system set-up description

FC hybrid system consists of a 1.2kW PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter connected to the FC, a bidirectional DC/DC converter connected to the batteries and programmable electronic load. The bus voltage between the two converters is 27V. The schematic diagram of hybrid system is shown in Figure 6-2. In the experiment, engine demand's load profile was implemented via the programmable electronic load. The PCI-6259 data acquisition (DAQ) was used to communicate between MATLAB and the hardware for sending and receiving data. The external connection, the NI SCB-68 connector block was used for interfacing I/O signals and to plug in data acquisition device via 68-pin connector. As was previously explained in Chapter 4, the SCB-68 rack can only accept voltage levels up to 10V so a voltage divider was used to step down voltages above 10V and the readings were then scaled back in the software. The current flowing through the various devices was sensed using numerous AMP25 Linear-to-60A Hall sensors. This hybrid system was used to validate the power demands simulation results of small UAV.

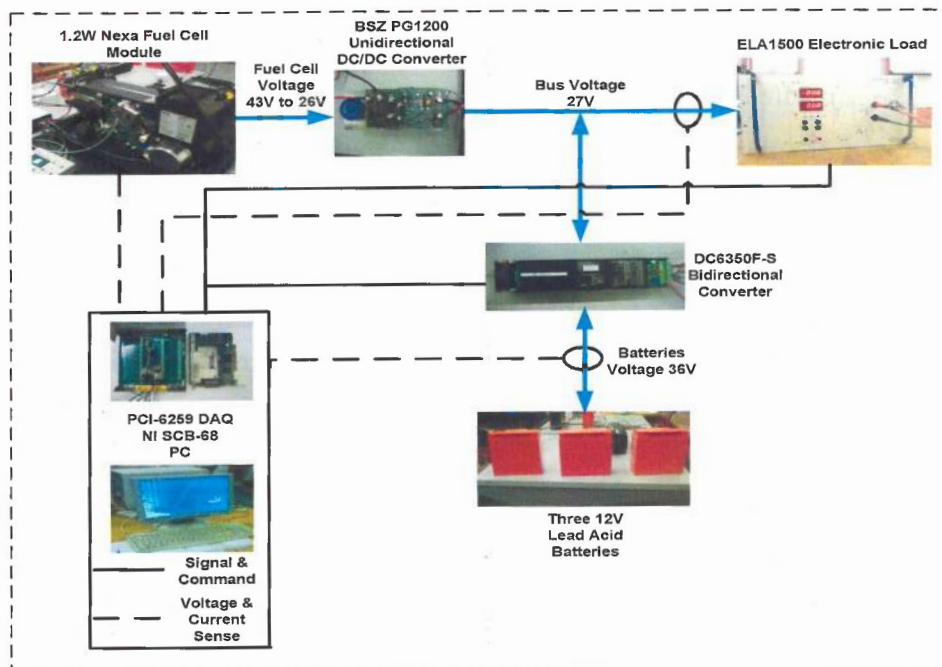


Figure 6-2. The schematic diagram of FC/batteries hybrid system

6.3 Simulation model of fuel cell/battery hybrid propulsion system

The simulation model of the hybrid system consisting of a 1.2kW PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter and electrical engine is shown in Figure 4-2, the model was developed in MATLAB/Simulink and description of each of blocks used in the model will be presented :

Fuel cell model: A dynamic model of 1.2kW PEMFC proposed by del Real et. al., was used as the basis in this study [39]. The model is based on semi-empirical principles derived from both theory and experimental results. Experimental data were obtained from a Nexa FC module. The data used as inputs to the PEMFC dynamic model were air pump voltage, fan voltage, ambient temperature, anode purge valve status and current demanded. The FC dynamic model was developed in MATLAB/Simulink environment. It consists of four main blocks: FC stack, air pump, cooling fan and hydrogen inlet. The FC stack is divided into three main modules: fluid dynamics module, electrochemical static module and thermal dynamics module. The fluid dynamics block consists of five interconnected sub-blocks which are the control volumes of two flow channels, the gas diffusion layers of the cathodes and anodes and the transport of the chemical species across the membrane. All of these are assumed to be at temperatures equal to the stack temperature. All terms of the electrochemical equation are presented in a novel way to optimizing and simplify its formulation. As a result the polarization curve is adapted to the corresponding experimental data by a direct algebraic algorithm. The thermal model is based on an air-cooled stack system, and takes into account the main terms of the overall energy balance. Full details of all model, included mathematical equations and parameters are described in Chapter 3.

DC/DC unidirectional converter model: A lookup table was formed to model DC/DC unidirectional converter BSZ PG 1200. The converter is connected to the Nexa FC and the input and output voltages of the converter were measured while varying the load current from 0A to 46A in steps of 2A.

DC/DC bidirectional converter model: The bidirectional buck-boost DC/DC converter circuit model was based on the half H-bridge topology as shown in Figure 6-3. The theory behind the buck and boost converters and the operation of switched-mode power supplies are described in **Appendix B**. The circuit has two sets of terminals, (see Figure 6-3), high voltage terminal V_{High} and a low voltage terminal V_{Low} . If a voltage source is applied to the high voltage terminal, then the converter will act as a buck or step-down converter and the output voltage on the low voltage terminal is equal to [68]:

$$V_{\text{Low}} = V_{\text{High}} D \quad (6.1)$$

Where D is the duty cycle of the PWM drive signal applied to the gates of the MOSFET in the converter, $D = t_{\text{on}}/T = t_{\text{on}}/(t_{\text{on}} + t_{\text{off}})$. t_{on} and t_{off} are the times when the signal is high and low respectively as shown in Figure 6-4. T is the total time and relates to the switching frequency $f_s = 1/T$. Similarly, the converter will act as a boost or step-up converter if the voltage is applied on the low voltage terminal. The output voltage on the high voltage terminal is equal to [68]:

$$V_{\text{High}} = V_{\text{Low}} \frac{1}{1-D} \quad (6.2)$$

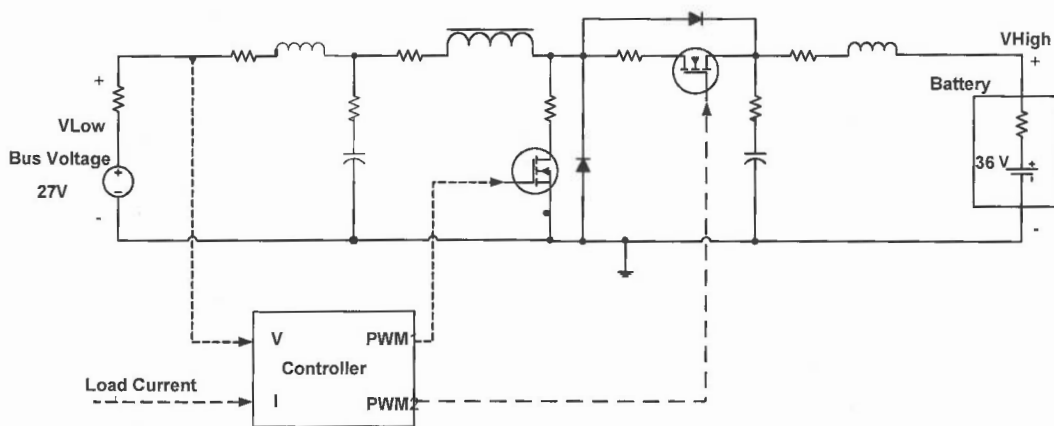


Figure 6-3. Bidirectional buck-boost DC/DC converter circuit diagram

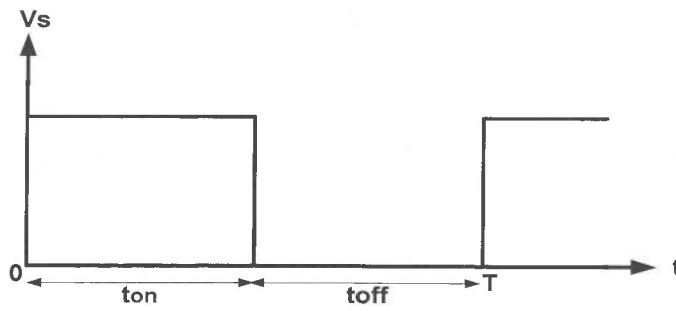


Figure 6-4. Switching signal in one Duty cycle

A current-mode controller as demonstrated by Chattopadhyay and Das was used to control the voltage and the current of the converter in each operating mode; buck or boost [69]. The current supplied to or from the converter is controlled and can be set to a fraction of the total load current. This is achieved by monitoring the load current and allowing the batteries and the FC to have different load sharing ratios. Switching the converter from one operating quadrant to another is done by changing the voltage setting of the converter. When the voltage of the converter is set slightly above the bus voltage (which set at 27V) the converter will act as a step down converter allowing the current to flow from the batteries to the load. Reducing the voltage of the converter slightly below 27V will cause the converter to act as a step up converter allowing the current to flow from the bus to the batteries.

Battery model: The battery block in Simulink SimPowerSystems® toolbox represents most popular types of rechargeable batteries, and was used in the hybrid simulation model. The specifications of the three rechargeable WP18-12 sealed lead acid batteries of 12 V and 18 Ah were programmed into the block.

Electrical engine model: The Dualsky XM5050CA DC engine was selected as the electric engine to power the PiperCub J3. The engine was tested for different throttle commands inputs. It was found that maximum engine power required 1290 Watts at 47.4A to generate the maximum RPM of 5460. Equation (6.3) is cubic basic fitting of the throttle vs current plot, which uses to calculate engine current demand.

$$Y = P_1 * X^3 + P_2 * X^2 + P_3 * X + P_4 \quad (6.3)$$

Where X is throttle commands (between 0% to 100%), and Y is the engine current demand. Coefficients: $P_1 = 8.5638 \times 10^{-5}$, $P_2 = -0.0066351$, $P_3 = 0.22221$, $P_4 = -2.7726$.

PiperCub J3 model: A non-linear 6 degree-of-freedom model with conventional high wing, positive dihedral configuration of the PiperCub J3 aircraft has been developed by de Lomas [70] and Thomas [71] with the intention to emulate accurate flight dynamic characteristics of the aircraft. The model has been subject to modifications with the replacement of the piston engine by an electrical motor.

The data obtained from the testing of the Dualsky XM5050CA DC engine were derived and integrated into the nonlinear model. It was hence possible to extrapolate the power demand (WATT) with respect to the generated RPM. In 6 DoF non-linear model the vehicle dynamics have been assorted into longitudinal and lateral dynamics, displaying the behaviour of the aircraft along each axis and thus allowing us to consider it as two 3 DoF systems with decoupled inertial frames, non linear velocity and angular rates.

Table 6-1 lists the main parameters of the aircraft including the total mass, centre of gravity position and servo rate. Figure 6-5 shows a representation of the plan in which the propulsion system is replaced by a FC propulsion system (fuel cell/battery/dc/dc converter and electrical engine).

Table 6-1. Piper Cub J3 aircraft model parameters

Wing span (m)	2.040
Aerodynamic chord (m)	0.3070
Wing reference area (m²)	0.6290
Aspect ratio	6.68
Engine power (KW)	1.29
Aircraft weight (kg)	5.65
CG (m)	0.31,0,0
Servo rate (°)	30
Servolimits (Ailerons, Elevator, Rudder) (°)	20,15,30

Expressions for aerodynamic coefficients are:

$$C_D = C_{D0} + C_{DM}M + C_{D\delta e}\delta_e + C_{D\alpha}2\alpha^2 + (C_L - C_{L0})^2 \frac{e}{\pi A} \quad (6.4)$$

$$C_Y = C_{Y\beta}\beta + (C_{Yp}p + C_{Yr}r)\frac{b}{2V} + C_{Y\delta_a}\delta_a + C_{Y\delta_r}\delta_r \quad (6.5)$$

$$C_L = C_{L\alpha}\alpha + C_{LM}M + C_{Lq}\frac{c}{2V} + C_{L\delta_a}\delta_a + C_{L\delta_e}\delta_e \quad (6.6)$$

$$C_1 = C_{1\beta}\beta + (C_{1p}p + C_{1r}r)\frac{b}{2V} + C_{1\delta_a}\delta_a + C_{1\delta_r}\delta_r \quad (6.7)$$

$$C_m = C_{m\alpha}\alpha + C_{mM}M + (C_{mq}q + C_{L\delta_a}\delta_a)\frac{c}{2V} + C_{m\delta_e}\delta_e \quad (6.8)$$

$$C_n = C_{n\beta}\beta + C_{na}a + C_{n\delta_r}\delta_r + (C_{np}p + C_{nr}r)\frac{b}{2V} \quad (6.9)$$

Where:

C_D Drag coefficient

C_L Lift coefficient

C_m Pitching moment coefficient

C_Y Lateral force coefficient

C_n Yawing moment coefficient

b Semi wing span

α Angle of attack

v Velocity

β Sideslip angle

$(\delta_r, \delta_e, \delta_a)$ Control surfaces deflection

M Mach velocity

(p, q, r) Aerodynamic rates along the axis

The equations of motion are used to calculate every parameter involved with the aircraft's movement along the x, y and z axes. The calculation of all forces and moments takes into account the aircraft characteristics such as inertia, mass, c.g., cp position and geometry.

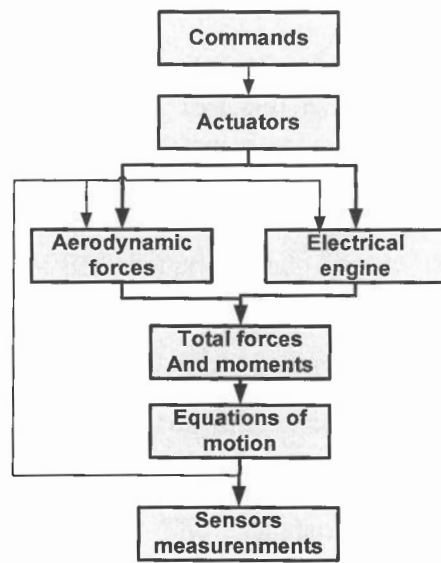


Figure 6-5. PiperCub J3 model

6.4 Chapter summary

This chapter presented the modified fuel cell hybrid system (see Figure 6-2). A bidirectional DC/DC converter and three 12V lead acid batteries were connected to the original system. The modification to the system had to be made in order to control the charging/discharging of the batteries and operate the system near optimal efficiency (this was not possible with the original Nexa system). The model for BSZ PG 1200 DC unidirectional convertor was formed through a series of lookup tables. The bidirectional buck-boost DC/DC converter circuit model was based on the half H-bridge topology. The circuit has two sets of terminals, high voltage terminal V_{High} and a low voltage terminal V_{Low} . The standard battery block in Simulink SimPowerSystems® toolbox was used to simulate the 12V lead acid battery. As for the electric engine model, the Dualsky XM5050CA DC engine variant was selected. The engine was tested under different throttle commands inputs and the recorded outputs were used to formulate the model. The next chapter will present the control strategies that were used to control the power from the FC and batteries during different flight phases with the aim of operating the system near maximum efficiency.

7 Energy Management

In this research study, the control strategy of the hybrid system for controlling the power between the FC and the battery is based on the following principle: The PEMFC is the main power supply for the electric engine driving the propeller and has to be operated at optimal efficiency. In the case that the FC cannot completely meet the power demands in any of the flight phases, the battery will provide short burst power demands as required. Simultaneously the FC should keep the battery adequately charged at all times. Figure 7-1 shows net system efficiency of the Nexa PEMFC as a plot of efficiency (% LHV) vs net current (Amps) and net power as a function of net current (Amps). The maximum Nexa system efficiency is about 50% at part load and drop to 38% at full power. All the goals above were achieved through control of the voltage and current of the step-down bidirectional DC6350F-S converter shown in Figure 7-2 (a).

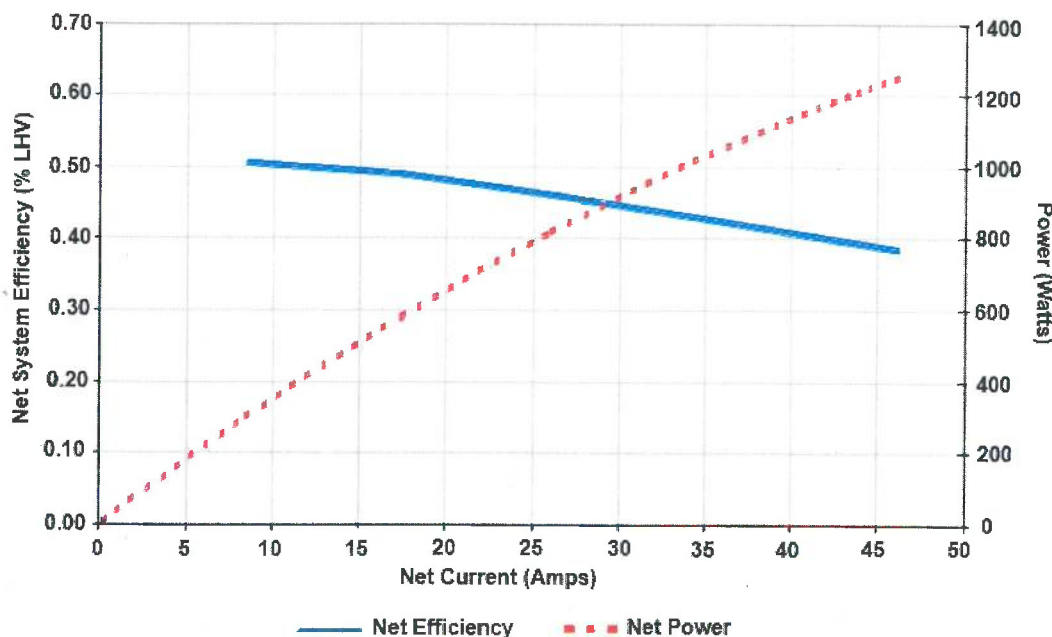
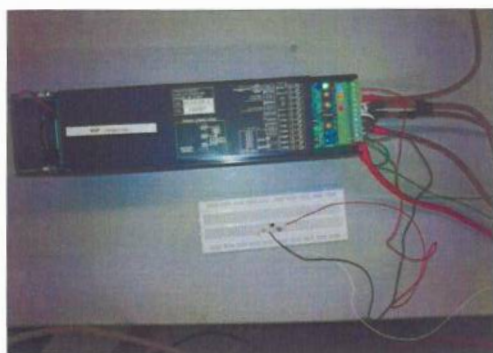
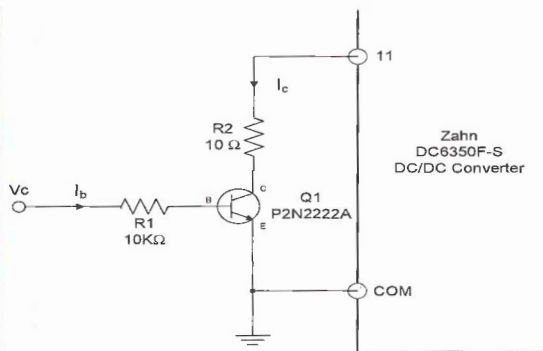


Figure 7-1. Nexa power module efficiency



7-2. (a) Bidirectional DC6350F-S converter, (b) The electrical circuit to vary the current limit at pin 11

Step down DC6350F-S VLP control

- Voltage control: +5V signal (sent from PC through SCB-68 rack) is used to vary the output voltage. The signal source is connected to pin 2 (V_{REF+}) and the common signal source is connected to pin 1 (com) of the control plug, which is the common converter. Varying the output voltage allowed control of the current flow direction, charging and discharging of the batteries.
- Current control: Controlling the current supplied by the converter was achieved by varying the current limit settings of the converter itself. The current limit can be varied via pin 11, connecting this pin to COM or ground will cause the converter to provide minimum or zero current while leaving it open or floating will cause the converter to supply maximum current. According to the manufacturer's data sheet pin 11 will source 13mA when it is shorted, thus by varying the value of this current the main current from the converter can be set to any desired value (using current mirror will not allow us to vary the current value). This can be achieved by means of a transistor as shown in the circuit illustrate Figure 7-2 (b). It consists of a BJT NPN transistor Q1 (general purpose P2N2222A) and two resistors R_1 and R_2 . A suitable value for R_1 was $10K\Omega$ to limit and protect the base terminal and to provide good control of the transistor's base current. A small value of 10Ω was chosen for R_2 to provide limited protection to the pin 11 of the converter and to ensure it does not exceed the rated current of 13mA. A voltage V_C (from PC through SCB-68 rack) is then applied to set the base current I_b which will then set the collector current I_c or the current supplied from pin 11. For the chosen

components V_C is calculated to vary from $\sim 1.25V$ which will set I_C to $13mA$ and will cause the converter to supply minimum or zero current and $0.6V$ which will set I_C to $\sim 0mA$ and will cause the converter to supply maximum current. Thus any value within this range can set the converter's current to any desired value while it is operating. The calculation of V_C is done by the following equations, neglecting R_2 and assuming the transistor has a current gain β of 200 and V_{be} of $0.6V$, these estimation values are taken from P2N2222A amplifier transistor datasheet. For I_C to be equal to $13mA$:

$$I_b = \frac{I_c}{\beta} = \frac{13mA}{200} = 65\mu A \quad (7.1)$$

$$V_c = I_b * R_1 + V_{be} = 65\mu A * 10\text{ k}\Omega + 0.6 = 1.25V \quad (7.2)$$

For I_C to be equal to zero, I_b has to be zero which leads to V_c to be equal to $0.6V$ or less.

7.1 Classical control

In a closed-loop system, a compensator operates on the error signal $e(t)$ and generates the actuation signal $u(t)$ to drives the plant as illustrated in Figure 7-3. There are many types of compensators, and a typical analog compensator has three basic operation modes:

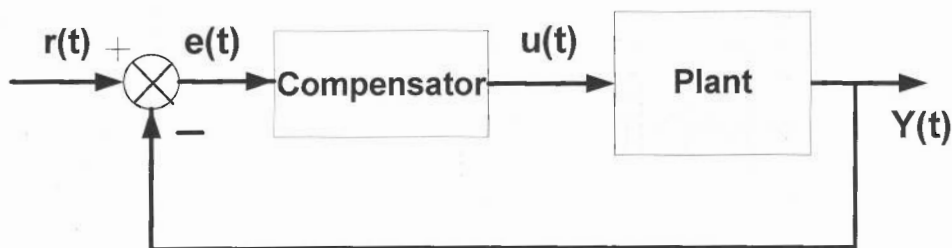


Figure 7-3. Closed-loop control system

Proportional action: In P control action, the actuation signal is proportional to the error signal, so that:

$$u(t) = K_p e(t) \text{ or } U(s) = K_p E(s) \quad (7.3)$$

Where K_p is proportional gain, low values of the proportional gain will give rise to a heavily damped response and a large steady-state error. Increasing the gain will speed up the system response and reduce both the damped and the steady-state error. More increases the gain will reduce the steady-state error and make the system too oscillatory [72].

Integral action: In I control action; the actuation signal is proportional to the time integral of the error signal:

$$u(t) = K_i \int_0^t e(t) dt \text{ or } U(s) = \frac{K_i}{s} E(s) \quad (7.4)$$

Where K_i is the integral gain. If value of $e(t)$ is constant and non-zero then the controller output $u(t)$ will be ramp. For zero controller input $e(t)$, the value of $u(t)$ remains stationary. I-action eliminates the steady state error, but it slows the closed-loop response, as result settling and rise times of the system increases.

Derivative action: With D control action, the actuation signal is proportional to the time derivative of the error signal. Thus,

$$u(t) = K_d \frac{de(t)}{dt} \text{ or } U(s) = sK_d E(s) \quad (7.5)$$

Where K_d is the derivative gain. D control action has no effect on steady-state error, when the rate of change of error is zero. But during transient it will tend to speed up the response times. This control is never used on its own. It used to complement P-action and I-action to give the full PID control action [72]. Prior description leads to complete three-term controller, its transfer function is:

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + sK_d \quad (7.6)$$

K_p = Proportional gain, selected adequate rise time

K_i = Integral gain, selected for steady-state accuracy

K_d = Derivative gain, selected to overcome excessive oscillation

Proportional-Integral (PI) control action: disadvantage of using P control action only is that the controlled variable is operated with an offset. Offset means steady-state deviation of the controlled variable from set point or simply steady-state error. thus, I action is adding to the P controller to remove the offset [73]. The controller becomes PI controller is described by:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt \quad \text{or} \quad u(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(t) dt \quad (7.7)$$

Where T_i is integral (or reset rate) time. Most often, the reset rate is the number of times per minute. PI controller has two parameters K_p and T_i to be tuned to obtain satisfactory control.

7.1.1 Design and implementation of the classical control

Implementing PI controller in Simulink: The simulations were first developed to study system behaviour when the system was subjected to test cycles purposely designed for load variation, as shown in Figure 7-4. The power demand is 800W at the beginning (in fact at the power load demand of 800W, the power taken from FC was 840W to also charge up the batteries). After 120 seconds the load power demand suddenly increased to 1500W, as result the FC output power increases to 1004W and remaining power is taken from the batteries, as shown in Figure 7-5.

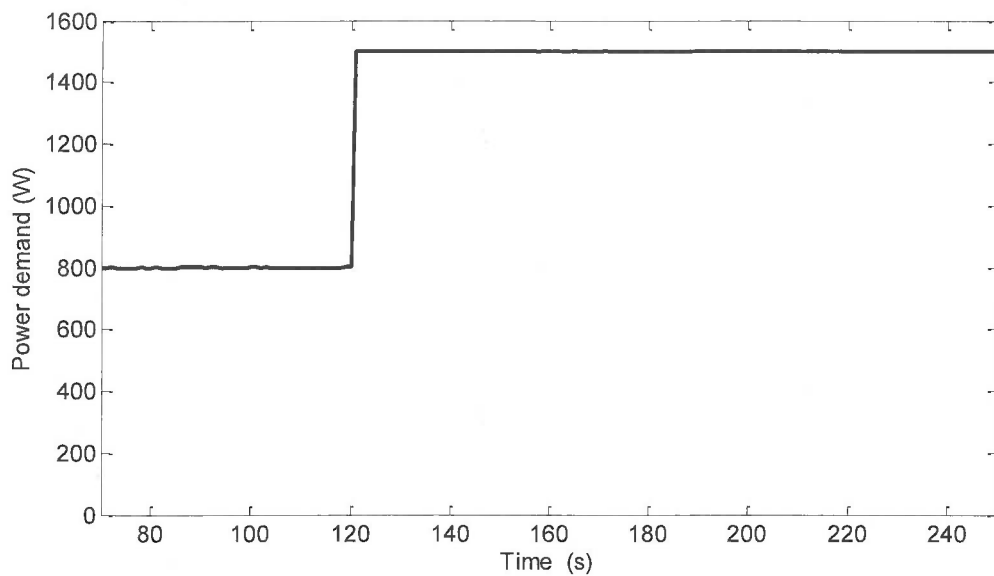


Figure 7-4. Load power

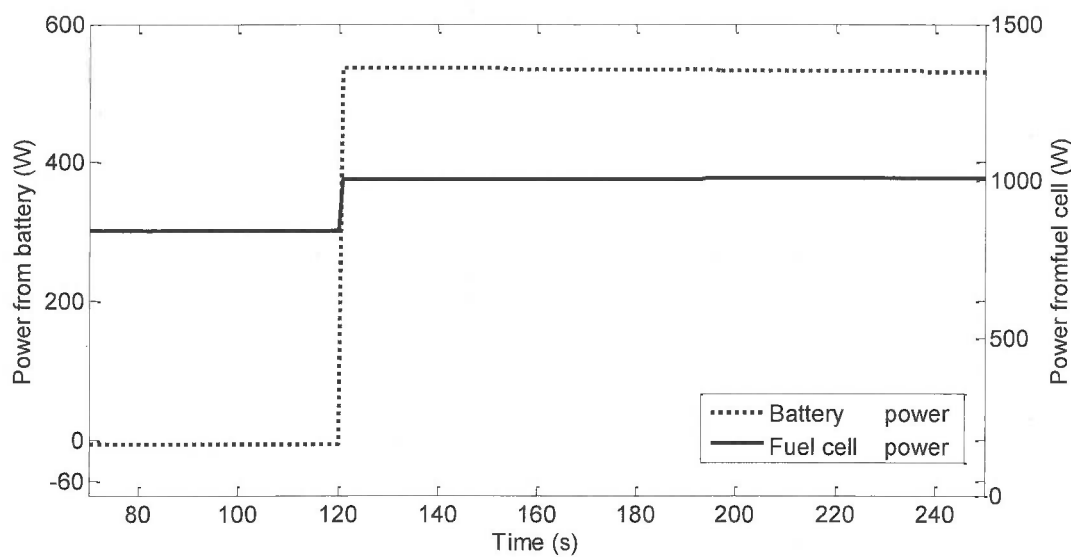


Figure 7-5. Output power from the FC and batteries without controller

In order to maximize the PEMFC power system efficiency, the optimal operation region of the FC system has to be achieved and maintained. It was decided that the best operating point of the Nexa fuel cell is 900W, of 48% of the efficiency (In this test the power demand reached around 1500W and maximum FC power is 1.2kW). A traditional PI controller was designed and implemented in the simulation to achieve that goal as illustrate in Figure 7-6. The two parameters of PI controller were tuned manually. Starting of the tuning was with set K_I to zero and then adjusted K_P . After

that increase K_I until offset was corrected in sufficient time for the system. The controller parameters selected were: $K_P = 1$ and $K_I = 0.1$. Figure 7-7 shows that output power from the FC is maintained at 900W when the power demand increase from 800W to 1500W at 120 seconds, the FC power response has very small drop and took 25 seconds to return to the optimal operating point while the remaining power is taken from the battery. Figure 7-8 shows the output in terms of current.

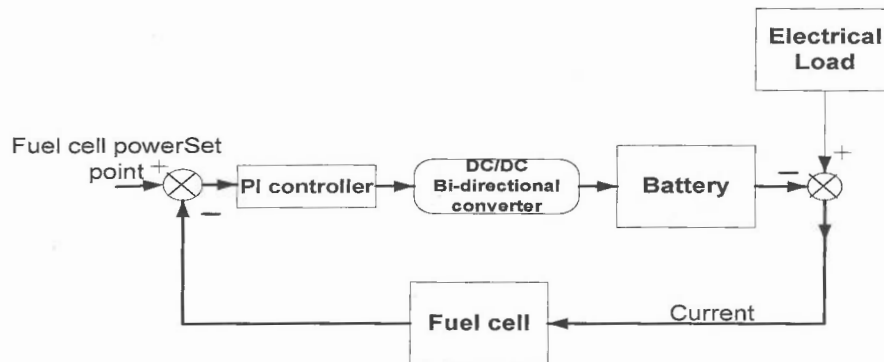


Figure 7-6. Schematic diagram of the PI controller

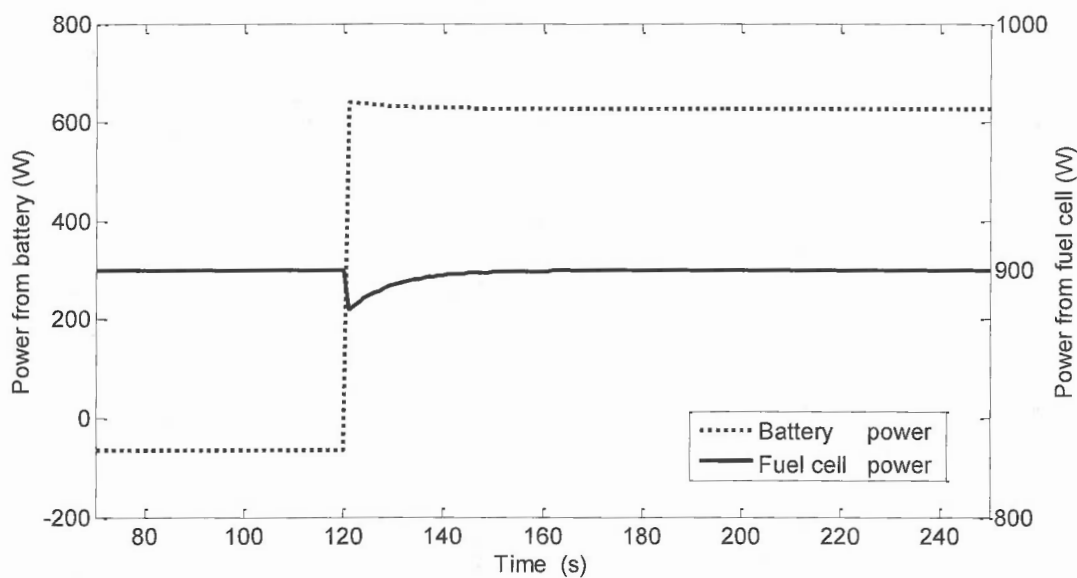


Figure 7-7. Output power from the FC and batteries with PI controller

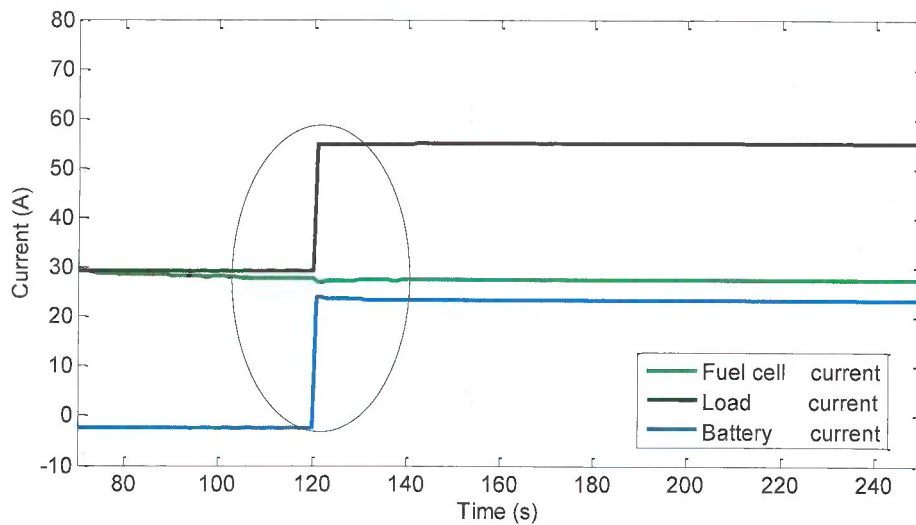


Figure 7-8. Output current from the FC and batteries with PI controller

PID controller hardware-in-the-loop implementation: The optimal operating region of the Nexa FC is in the range between 8A to 29A, (see Figure 7-1). During hardware-in-the-loop testing a differential component was found to be necessary to maintain performance. Therefore, a PID controller was designed and implemented in hardware-in-the-loop to control the battery current in FC/battery hybrid system which was described in Section 6.2, controller schematic diagram is illustrated in Figure 7-9. For safety considerations, a saturation block is located between the controller and DC converter. The controller parameters were tuned manually and they are: $K_P = 0.003$, $K_I = 0.0001$ and $K_D = 0.001$. The load current was step changed at $t = 615$ seconds, $t = 731$ seconds and $t = 861$ seconds between 5A and 35A as shown in Figure 7-10. With each step change it can be seen that the current drawn from the FC followed the load current, while the battery current showed a significant delay. In fact the batteries took about 10 seconds to supply around 10A. This was due to the controller's integral component which introduced a lag into the closed loop system, but could not be removed as it was necessary for minimising steady-state error.

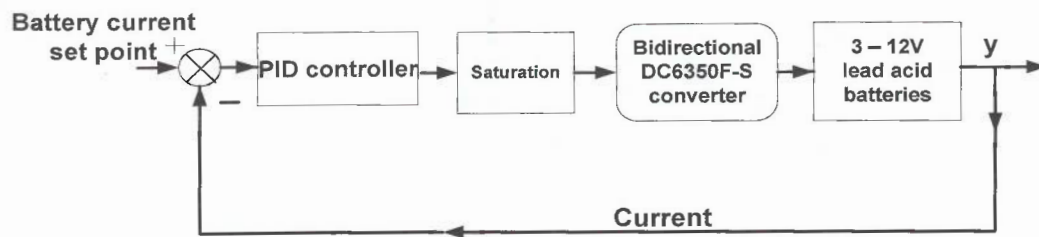


Figure 7-9. Schematic diagram of the PID controller

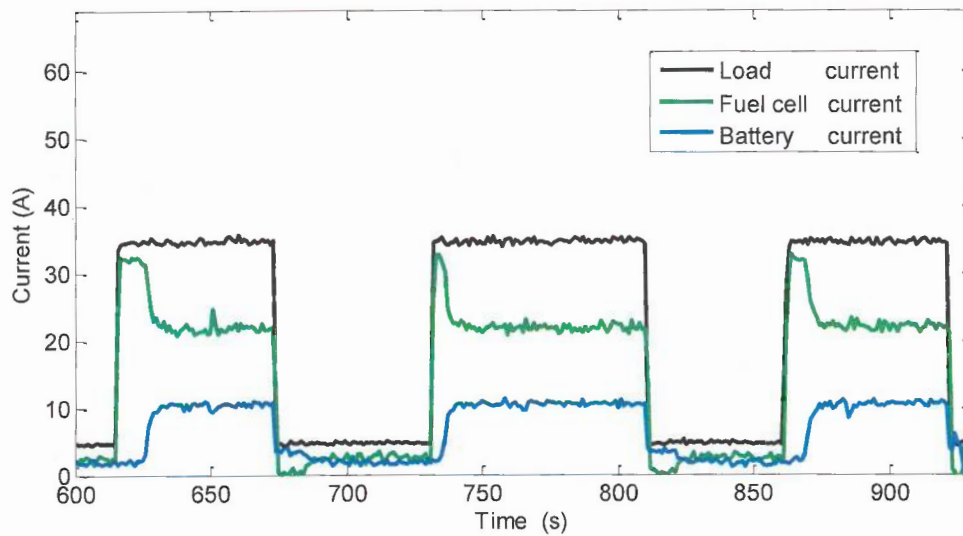


Figure 7-10. Load, fuel cell and battery step current with PID controller

To improve the PID controller response, a basis was added to the control loop between the controller and bidirectional DC converter as shown in Figure 7-11. The test was then repeated with the same controller parameters: $K_P = 0.003$, $K_I = 0.0001$ and $K_D = 0.001$. Figure 7-12 shows the load current was varied at $t = 824$ seconds, $t = 945$ seconds and $t = 1076$ seconds from 5A to 35A. With each step change it can be seen that the current drawn from the FC followed the load current with small overshoot, while the battery current showed a very small delay compare with controller without basis. The batteries current response takes about 2 seconds to supply around 10A.

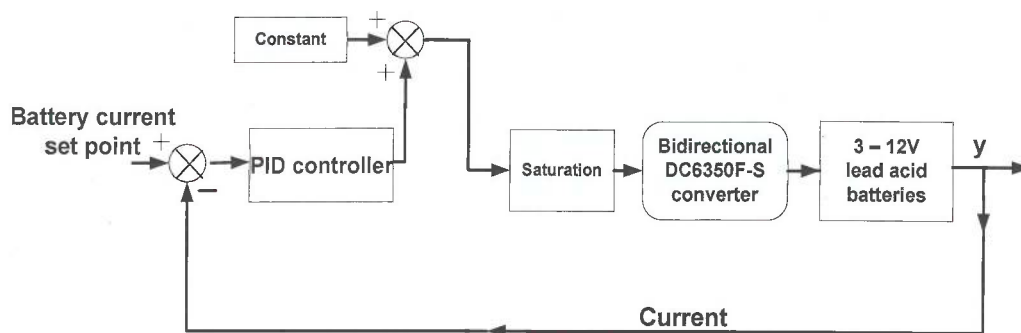


Figure 7-11. Schematic diagram of the PID controller with basis

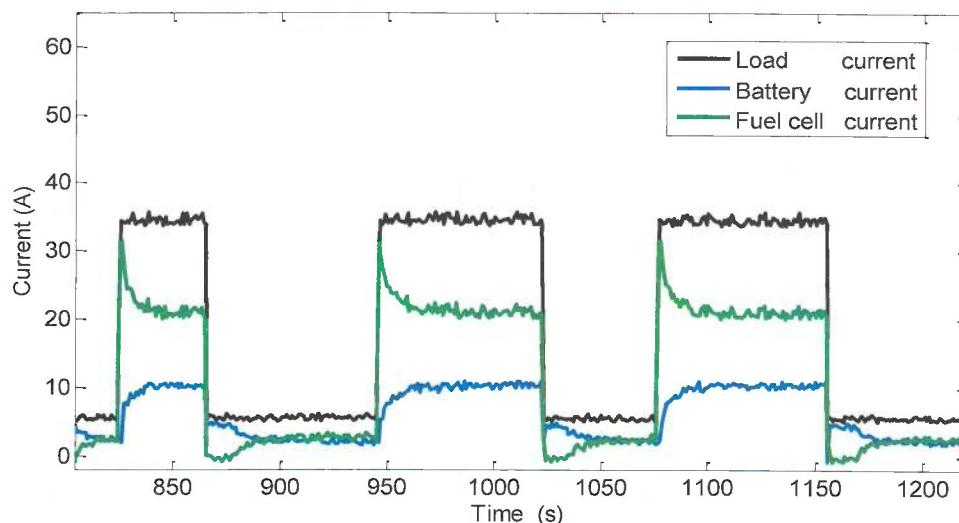


Figure 7-12. Load, fuel cell and battery step current with PID controller with basis

The PID response was acceptable, however, a more advanced controller was needed to provide better and faster response time. A feed-forward fuzzy logic controller was chosen, since the feed-forward output is not affected by the system feedback, it will not cause the control system to oscillate. This improved the system response and stability. It will be described in more detail, along with the experimental verification in the next section of this thesis.

7.2 Fuzzy logic control

Zadeh is credited with introducing fuzzy set theory on which is the basic for fuzzy logic (FL) control [74]. The fuzzy set theory was initially presented as a means of dealing with non-crisp data sets and only later developed as a control methodology [75]. It was not until computer power had developed sufficiently to cope with large matrices (1970s) that set theory applied in practice to control systems [76]. One of the first applications of fuzzy logic to control (of a steam engine) was by King and Mamdani [77], [78]. Since then fuzzy logic had been widely applied in control applications

In the present project we examine the application of fuzzy logic for managing the power flow between two sources in an aircraft. There are many reports in the literature of the successful application of fuzzy logic to power sharing between different sources in automotive applications [66], [67], [79], [80], [81], [82] and [83]. The output of the fuzzy logic controller is typically related to the input by the rule IF X AND Y THEN Z. The IF part (antecedent) defines the state of the input variables and the THEN (consequent) gives the value of the output variable [81]. The fuzzy logic is suitable for processes with complex non-linear models, empirically-based, relying on the experience of the operator rather than their technical understanding of the system.

7.2.1 Fuzzy sets

In a crisp set S , an element is either a member of the set $x \in u$ or not a member of the set $x \notin u$ (where u is called the universe of discourse). But in real life this is not the case elements may not fall neatly into a single category. With fuzzy sets it is usual to define a function called as "membership function" ($mf \leq 1$) which defines the degree of membership of the element. More formally: a set S is fuzzy if it is paired with a membership function $u_s : u [0,1]$ which, given an element $x \in u$, defines its degree of membership of S . The membership function is invariably written as:

$$u_s(x) = \begin{cases} 1, & \text{if } x \in S \\ 0, & \text{if } x \notin S \end{cases} \quad (7.8)$$

Consider the example of “cold” and “cool” water as defined in the crisp Equation (7.9) and Figure 7-13. The transition from “cold” to “cool” is clear and precise. A small fraction of a degree moves an element from one set to the other. Certainly, one would expect that water at temperature -10°C is much colder than that at 1°C . Water at temperature -10°C is rather frozen than cold. Similarly, water at temperature 10°C is much hotter than that at 0°C . On other hand, using the application of a single degree Celsius is not accurate to define a transition from cold to cool. In the real world, the transition between “cold” and “cool” is gradual and smooth for many practical reasons: is the temperature being measured the true bulk temperature of the water, how accurate is the measuring device, etc. [75]. The formal classification of Equation (7.9) does not allow for practical consideration.

$$\begin{aligned} u_{\text{cold}}(t) &= \begin{cases} 1, & \text{if } -10^{\circ}\text{C} \leq t \leq 0^{\circ}\text{C} \\ 0, & \text{otherwise} \end{cases} \\ u_{\text{cool}}(t) &= \begin{cases} 1, & \text{if } 0^{\circ}\text{C} \leq t \leq 10^{\circ}\text{C} \\ 0, & \text{otherwise} \end{cases} \end{aligned} \quad (7.9)$$

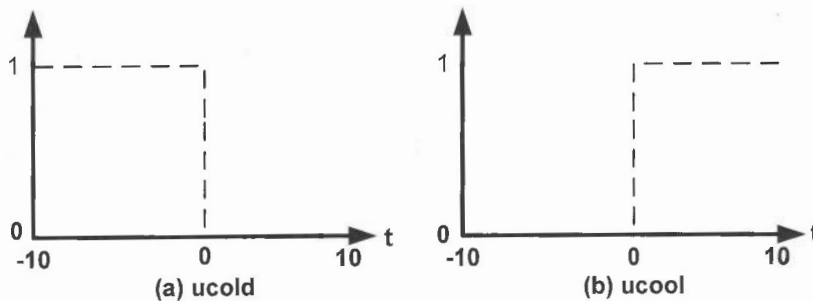


Figure 7-13. The representation of the crisp definition, (a) cold water concept and (b) cool water concept

The membership function of fuzzy sets can be described in many different ways. Triangular and trapezoidal functions are commonly used in fuzzy logic control. For example, Equation (7.10) applies a triangular membership function to the concepts of “cold” and “cool” water as depicted in Figure 7-14.

$$\begin{aligned}
 u_{\text{cold}}(t) &= \begin{cases} \frac{2}{15}t + \frac{5}{3}, & \text{if } -12.5^\circ\text{C} < t \leq -5^\circ\text{C} \\ -\frac{2}{15}t + \frac{1}{3}, & \text{if } -5^\circ\text{C} < t \leq 2.5^\circ\text{C} \\ 0, & \text{otherwise} \end{cases} \\
 u_{\text{cool}}(t) &= \begin{cases} \frac{2}{15}t + \frac{1}{3}, & \text{if } -2.5^\circ\text{C} < t \leq 5^\circ\text{C} \\ -\frac{2}{15}t + \frac{5}{3}, & \text{if } 5^\circ\text{C} < t \leq 12.5^\circ\text{C} \\ 0, & \text{otherwise} \end{cases}
 \end{aligned} \tag{7.10}$$

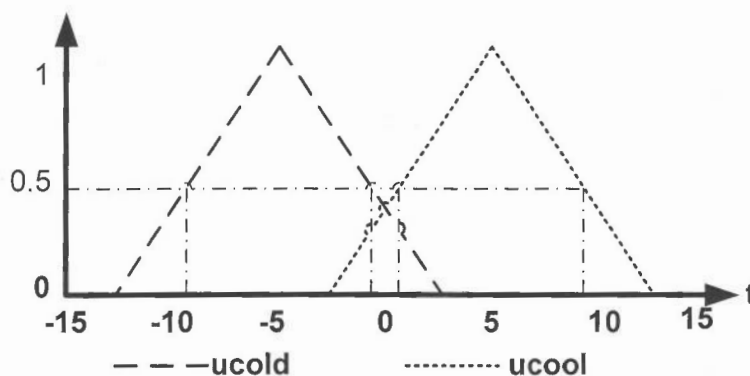


Figure 7-14. The triangular fuzzy representation of cold and cool water concepts

7.2.2 Fuzzy set operation

There are several operators such as intersection, union and complement which operate on the fuzzy sets.

Fuzzy set intersection: The intersection operation ($\cap$ or logical AND connective) is required to meet the following conditions:

- | | |
|---|-----------------|
| $A \cap 1 = A$ | (Identity) |
| $A \cap 0 = 0$ | (Absorption) |
| $A \cap B = B \cap A$ | (Commutativity) |
| $A \cap (B \cap C) = (A \cap B) \cap C$ | (Associativity) |

Where: A, B and C are fuzzy sets and their membership functions are u_A , u_B and u_C respectively. For example, the intersection of fuzzy sets of A and B is equal to fuzzy set C:

$$C = A \cap B$$

The membership function is:

$$u_C(x) = \min [u_A(x), u_B(x)] \quad \text{or} \quad = u_A \cap u_B \quad (7.11)$$

The green area of Figure 7-15 displays the intersection of fuzzy sets A and B.

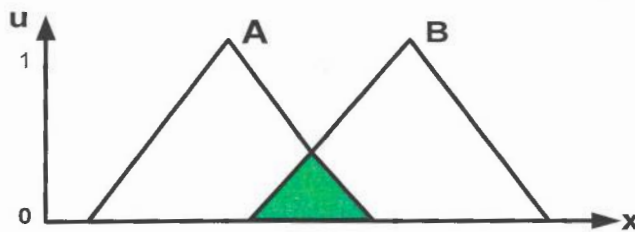


Figure 7-15. The intersection of fuzzy sets A and B

Fuzzy set union: The union operation ($\cup$ or the logical OR connective) is similar to the intersection that it is required to meet the following conditions:

- $A \cup 0 = A$ (Identity)
- $A \cup 1 = 1$ (Absorption)
- $A \cup B = B \cup A$ (Commutativity)
- $A \cup (B \cup C) = (A \cup B) \cup C$ (Associativity)

The union of fuzzy sets of A and B is equal to fuzzy set C:

$$C = A \cup B$$

The membership function is:

$$u_C(x) = \max [u_A(x), u_B(x)] \quad \text{or} \quad = u_A \cup u_B \quad (7.12)$$

The green area of Figure 7-16 displays the union of fuzzy sets A and B.

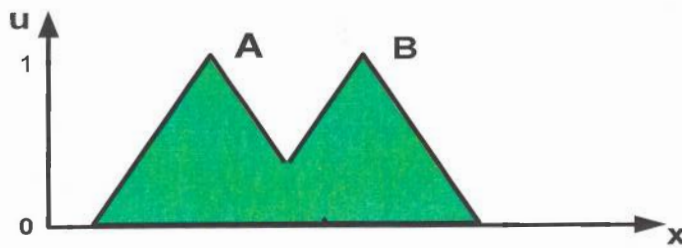


Figure 7-16. The union of fuzzy sets A and B

Fuzzy set complement: consider a fuzzy set A in a universe X: its complement is fuzzy set $\bar{A}$ which is defined by following membership function:

$$u_{\bar{A}}(x) = 1 - u_A(x) \quad (7.13)$$

There are natural conditions to impose on the complement:

$$\bar{\bar{0}} = 1 \quad (\text{Complementation})$$

$$A < B \Rightarrow \bar{A} > \bar{B} \quad (\text{Monotonicity})$$

$$\bar{\bar{A}} = A \quad (\text{Involution})$$

The dotted line of Figure 7-17 displays the complement of fuzzy set A.

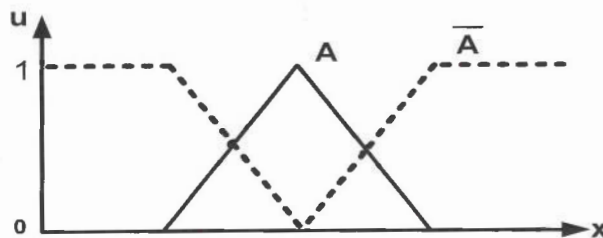


Figure 7-17. The complement of fuzzy set A

Cartesian product: If $A_1, \dots, A_n$, are fuzzy sets in $U_1, \dots, U_n$ respectively. The product of $A_1, \dots, A_n$ is fuzzy set in the product space $U_1 \times \dots \times U_n$ with the membership:

$$\mu_{A_1 \times \dots \times A_n}(u_1, u_2, \dots, u_n) = \min(\mu_{A_1}(u_1), \dots, \mu_{A_n}(u_n)) \quad (7.14)$$

7.2.3 Extension principle and fuzzy numbers

Extension principle is providing a means for the extension of the binary arithmetic operations of addition, multiplication, subtraction and division from simply operating on numbers to be applicable to fuzzy numbers which are fuzzy subsets of the real line [85]. Also the operation of a mathematical function on fuzzy sets can be defined by it. To understand the idea behind the principle, let assume X and Y are two standard sets. Let f be a point mapping from X to Y , that is $f: X \rightarrow Y$ such that for each $x \in X$, $f(x) = y$, where $y \in Y$ such that if A is a fuzzy subset of X then $f(A) = B$, where B is a fuzzy subset of Y defined by:

$$B = \bigcup_{x \in X} \mu_A(x) / f(x) \quad (7.15)$$

On the other hand it can be seen that for each $y \in Y$,

$$B(y) = \max_{\substack{\text{all } x \in X \\ \text{for which} \\ f(x)=y}} \mu_A(x) \quad (7.16)$$

With the understanding that if there exists no $x \in X$ such that $f(x) = y$, then $B(y) = 0$. Note that if $A = \mu_{x^*}$ then $A(\mu_{x^*}) = 1$ and $A(\mu_{x^*}) = 0$ for all $x \neq x^*$, and then:

$$B = \mu_{f(x^*)} = \mu_{f(x^*)} \quad (7.17)$$

A justification and another characterization of this principle will be given. This justification is based upon using a relationship to represent the mapping f . Any

mapping f from X to Y can be represented as a relationship on the cartesian space $X * Y$. That is, f can be represented as a subset of the cartesian product $X * Y$, denoted F , such that $(x, y) \in F$ if $f(x) = y$ and $(x, y) \notin F$ if $f(x) \neq y$. In terms of characteristic functions, $F(x, y) = 1$ if $y = f(x)$ and $F(x, y) = 0$ if $y \neq f(x)$. We note that a map is a special relationship in which for each $x \in X$ there exists one and only one tuple containing x as the first element, according to the above definition F and f are equivalent entities.

7.2.4 Fuzzy relation

The fuzzy relation is introduced in fuzzy set theory as generalisation of conventional relations. This relation can be considered as a set of tuples where a tuple is an ordered pair. As one can guess, a fuzzy relation R^f create the degree to which an element $a \in A$ is related to element $b \in B$ with respect to relation R^f . as a result fuzzy relation can be viewed as a crisp set of all pairs $((a, b), \mu_{R^f}(a, b))$ where (a, b) is any pair of $A \times B$. Fuzzy relation $R^f: A \rightarrow B$ can also be viewed as a $|A| \times |B|$ matrix with same name wherein $R_{ij}^f = \mu_{R^f}(i, j)$.

Composition of relation is computed using the so-called min-max rule[20, 21]. Let $\bullet$ be the composition operator of fuzzy relation. Assume $R: A \rightarrow B$ and $S: B \rightarrow C$ be two fuzzy relations. The membership function μ_T of fuzzy relation $T: A \rightarrow C$ such that $T = R \bullet S$ is computed as in Equation (7.18) for all $a \in A$ and $c \in C$.

$$\mu_T(a, c) = \max_{b \in B} (\min(\mu_R(a, b), \mu_S(b, c))) \quad (7.18)$$

Operations on fuzzy relation: R^f and S^f are fuzzy relations on the Cartesian space $X \times Y$. Then the following operations apply for the membership values for various set operation:

$$\text{Union} \quad \mu_{R^f \cup S^f}(x, y) = \max(\mu_{R^f}(x, y), \mu_{S^f}(x, y)) \quad (7.19)$$

$$\text{Intersection} \quad \mu_{R^f \cap S^f}(x, y) = \min(\mu_{R^f}(x, y), \mu_{S^f}(x, y)) \quad (7.20)$$

$$\text{Complement} \quad \mu_{R^f}(x, y) = 1 - \mu_{R^f}(x, y) \quad (7.21)$$

$$\text{Containment} \quad R^f \subset S^f \Rightarrow \mu_{R^f}(x, y) \leq \mu_{S^f}(x, y) \quad (7.22)$$

7.2.5 Fuzzy controller

A generic architecture of the fuzzy controller is shown in Figure 7-18 where four principal components can be identified: a fuzzification interface, a knowledge base, the inference and a defuzzification interface. Usually three steps are needed for designing fuzzy controller:

- 1- Fuzzification process is responsible of encoding the crisp measure values of the system parameter into linguistic values using the respective membership functions.
- 2- Inference uses the knowledge base of rules to determine the output fuzzy sets for the input linguistic values.
- 3- Defuzzification is the reverse process of the fuzzification. It is decoding the output fuzzy set of the inference process into crisp values.

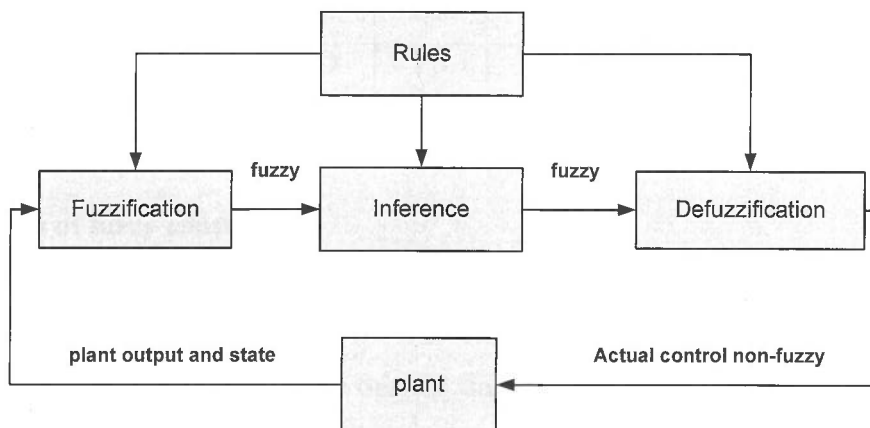


Figure 7-18. Generic architecture of fuzzy logic controller in feedback control loop

The fuzzy logic is suitable for modelling complex non-linear process, empirically-based, relying on the experience of the operator rather than the technical understanding of the system. An example of a matrix of 49 rules is in Table 7-1, it covers all possible combination of fuzzy sets for two input variables. Each variable has seven fuzzy sets. The rules describe a PDFLC (a proportional-derivative fuzzy logic controller), and are presented as:

R_N : If error is E_i and change in error is ΔE_j then output is U_{ij}

Where $1 \leq N \leq$ number of sets for error multiplied by the number of set for change in error. $1 \leq i \leq$ number of sets for error. $1 \leq j \leq$ number of sets for change in error.

E_i and ΔE_j are fuzzy sets of error and change in error, respectively. U_{ij} is the output fuzzy sets. The notation meaning in Table 7-1 are:

PB $\rightarrow$ positive big, PM $\rightarrow$ positive medium, PS $\rightarrow$ positive small, ZO $\rightarrow$ zero

NS $\rightarrow$ negative small, NM $\rightarrow$ negative medium, NB $\rightarrow$ negative big

Table 7-1. Rule matrix

		Error						
Change in Error		NB	NM	NS	ZO	PS	PM	PB
	NB	NB	NB	NB	NB	NM	NB	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

Advantages of fuzzy controller:

- Fuzzy controllers are more robust and stable than traditional PID controllers (Mamdani), because they can operate in the presence of noise and other disturbances and cover a greater range of operating conditions than PID controllers.
- Fuzzy controller usually cost less to develop than model-based or conventional controller doing the same task.
- Fuzzy controllers are relative easy to understand and to modify their rules, and how of operation.
- Fuzzy logic control rules are expressed in linguistic terms and use the human operator's experience.

7.2.6 Design and implementation of the fuzzy logic controller

The schematic diagram in Figure 7-19 shows the fuzzy logic controller used in hardware-in-the-loop to manage the power between two sources: FC and batteries. The controller has two input variables and one output variable. The input variables are the electrical engine power demand and the battery state of charge (SoC) represented by the battery voltage. If the total battery voltage was less than 30V the battery needed to be charged. Here 33V and 36V or more correspond to 50% and 100% SoC, respectively. The output variable is the bidirectional DC/DC converter output power (how much current to be supplied to or from the batteries). The membership functions of the fuzzy sets (inputs and output) are shown in Figure 7-20, and the fuzzy logic controller surface of the present implementation is shown in Figure 7-21. For instance, IF the power demand is high and battery SoC is high THEN the battery will supply power to assist the FC to operate with high efficiency. When the power demand is low and the battery's SoC is low THEN the FC supply power for the engine and charging up the battery through the bidirectional DC/DC converter (battery maximum charging current is -5.4A). The rules of fuzzy logic controller are in **Appendix C**. The controller maintains FC operation at a high optimal efficiency.

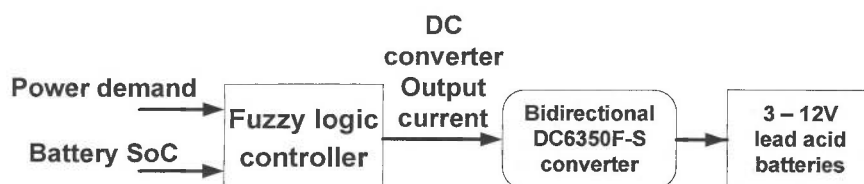


Figure 7-19. Schematic diagram of the fuzzy logic controller

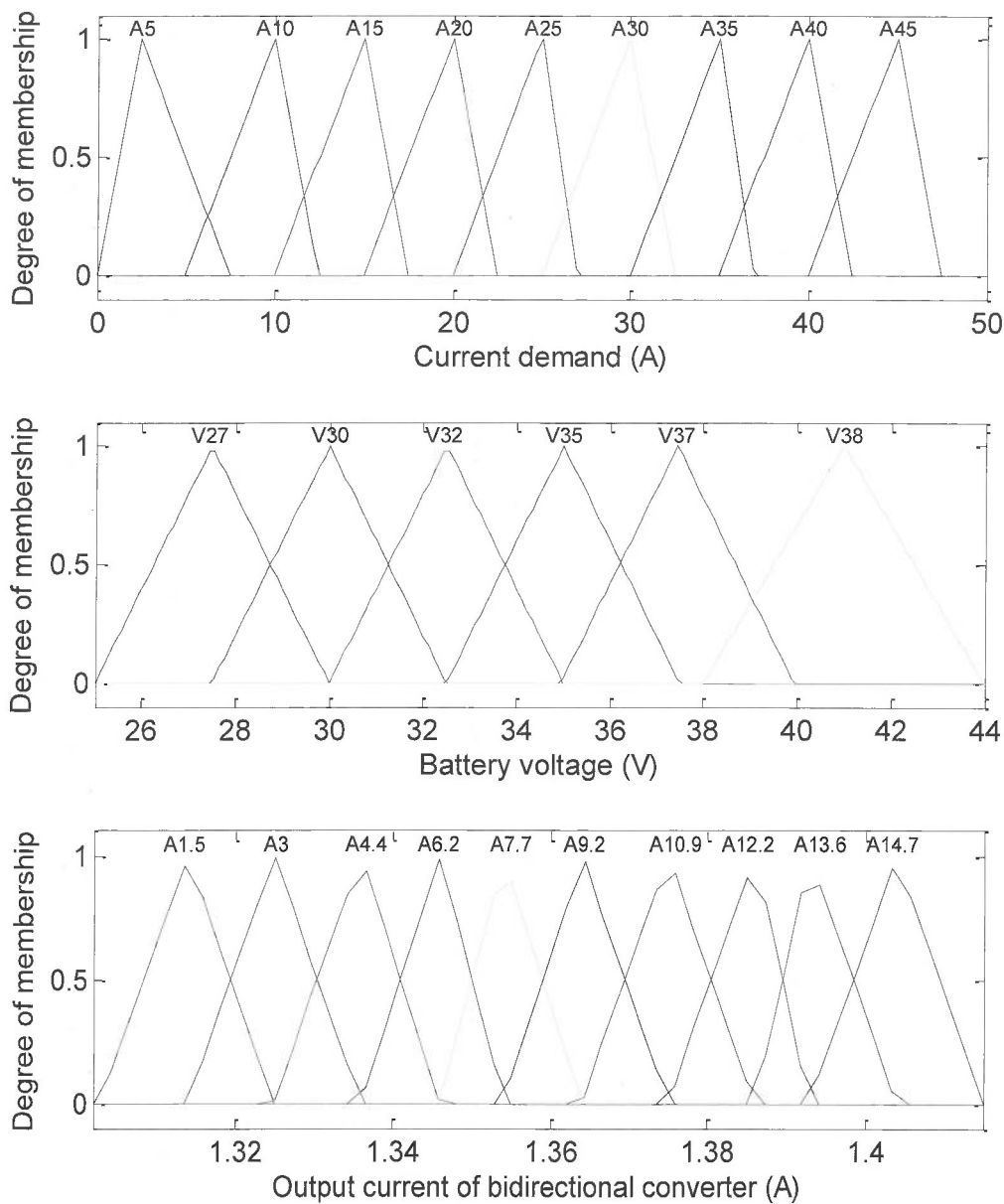


Figure 7-20. The input and output membership of the fuzzy logic controller

Replacing the PID controller with the fuzzy logic controller decreased the time constant of the system and enabled the battery current to reach its set point without any delay. The fuzzy logic controller guarantees a more stable and dynamic operation of the hybrid system. In the test, the load current was stepped from 0A to 30A at $t = 100$ seconds, $t = 130$ seconds and $t = 190$ seconds as shown in Figure 7-22. In every time while the load current increased in one step, it appears that the battery current adheres to the transient response without any delay to supply about 10A - the FC optimum is reached at 20A (see Figure 7-1).

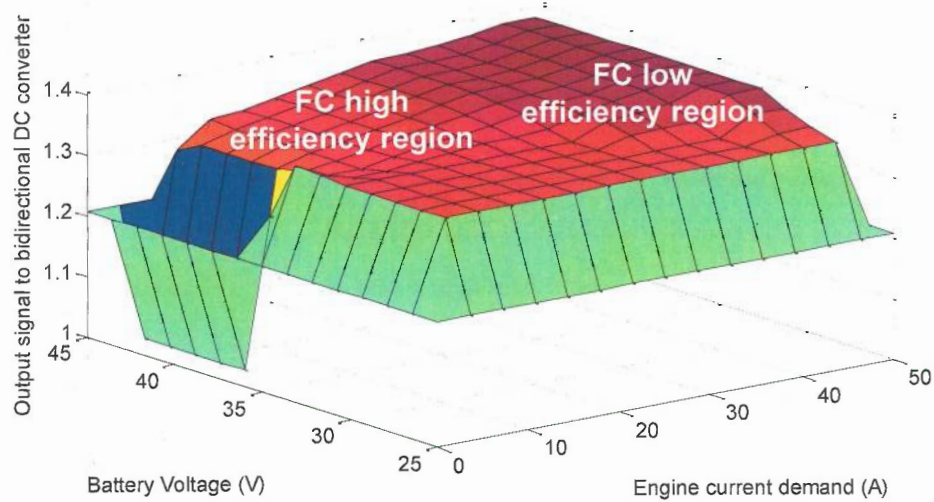


Figure 7-21. Surface viewer of the fuzzy logic controller

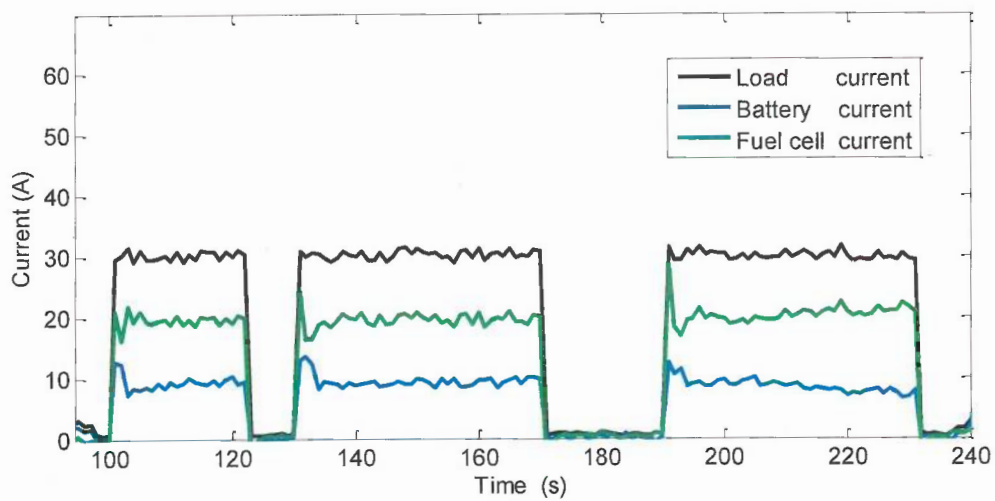


Figure 7-22. Load, FC and battery step current with fuzzy logic controller

7.3 Chapter summary

To manage the power between the FC and the battery in the hybrid system the first strategy was to develop a classical PID controller to study the system behaviour when the system was subjected to test cycles designed for load variation. The PID response was satisfactory by adding a basis for initial condition; however a more advanced controller was needed to provide faster response time.

A feed-forward fuzzy logic controller was chosen, since the feed-forward value alone can regularly provide the major portion of the controller output. The FLC has two input variables the electrical engine power demand and the battery state of charge represented by the battery voltage, and one output variable is the bidirectional DC/DC converter output power (how much current to be supplied to or from the batteries). The results showed that when the load current increased in one step, the battery current adheres to the transient response without any delay to supply about 10A - the FC optimum is reached at 20A.

8 Case Study Results and Discussion

This chapter will present three case studies that were used to validate and assess the performance of the modified hybrid system, including worst case scenario. In all three cases the fuel cell act as the main power source for the PiperCub J3 aircraft, with the battery acting as a secondary assisting source.

In the first flight scenario the mission was performed with no controller; whereas in the second case study the fuzzy logic controller was implemented to manage the power between the two sources and meet the power demand for the different phases of flight.

8.1 Case study I

Experiments were carried out in order to investigate the performance of the Nexa hybrid system (FC/battery) as the main power source for the PiperCub J3 aircraft. The flight scenario to investigate the feasibility of using the Nexa FC/battery hybrid to satisfy the power requirements of the aircraft included take-off, climb, cruise, descent and landing. In this case study, the electric hybrid system consists of a 1.2kW proton exchange membrane FC, a unidirectional step-down DC/DC converter and two 12V batteries driving an electrical engine as shown in Figure 8-1. As mentioned previously a Dualsky XM5050CA DC motor was selected to drive the PiperCub J3. The unidirectional DC converter is connected such that it maintains the output voltage from the FC at 27V. The rechargeable batteries at the converter output guarantee a stable and dynamic operation of the hybrid system. The power delivered to the electrical motor will be from both the FC and battery or from only one of them depending on the power demands. If the battery voltage drops, the FC charges up the batteries at the same time as it delivers power to the load via converter. The engine demand load profile was implemented in the programmable electronic load, the flight simulated path is shown in Figure 8-2. The aircraft climbs to a height of 10m and performs a circuit with a radius of 30m before returning to land.

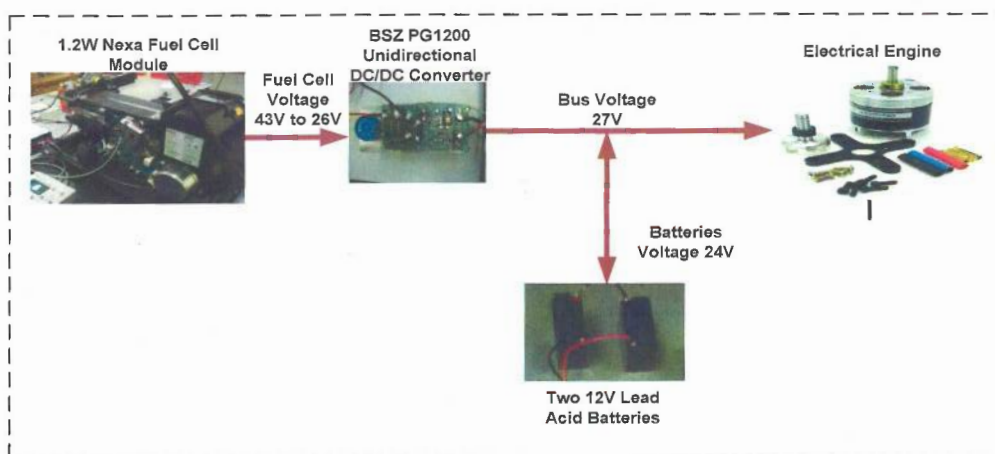


Figure 8-1. Nexa FC/battery propulsion system in case study I

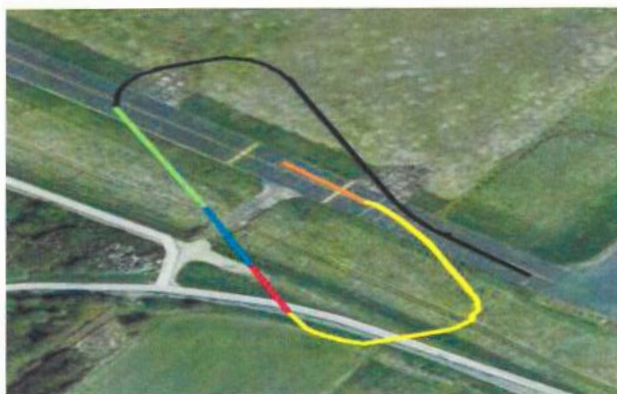


Figure 8-2. Flight path for case study I

Table 8-1 illustrates the maximum power demands for each stage of the flight. A minimum power demand is considered when the engine is idling with 0% throttle for the first 15 seconds, while maximum power demands occurred during the take off and climb stages with 100% throttle command. These two stages appeared at $t = 15$ seconds and $t = 158$ seconds respectively. For the other three stages, cruising at $t = 107$ seconds, descent at $t = 132$ seconds and landing at $t = 225$ seconds the aircraft required 951W, 402W and 172W, respectively.

Table 8-1. Power demands of flight phases for case study I

Throttle command (%)	Phases of flight	Require power (W)	Simulation time (s)
0 %	Idle	17	0-15
100%	Take off	1285	15-107
69%	Cruising	951	107-132
50.6%	Descent	402	132-158
100%	Climb	1285	158-225
39%	Landing	172	225-300

8.2 Results and discussion of the case study I

This first case study focuses upon using the Nexa hybrid system to meet the electrical engine power demands of the PiperCub J3 model without a controller. In this hybrid system, the DC/DC converter is connected such that it maintains the output voltage from the FC at 27V. The rechargeable batteries at the converter output guarantee a stable and dynamic operation of the hybrid system, see Figure 8-1. The power requirement for the engine is a function of throttle commands for the various flight phases. Figure 8-3, is a plot of throttle commands while Figures 8-4 and 8-5 show the corresponding power and current demands from the engine. For the first 15 seconds, the engine is at idle and requires 17W as shown in Figure 8-4, which is entirely provided from the FC. In this period the additional power from the FC is used to charge the battery as shown in Figure 8-8, where negative battery current in the figure corresponds to the battery being charged.

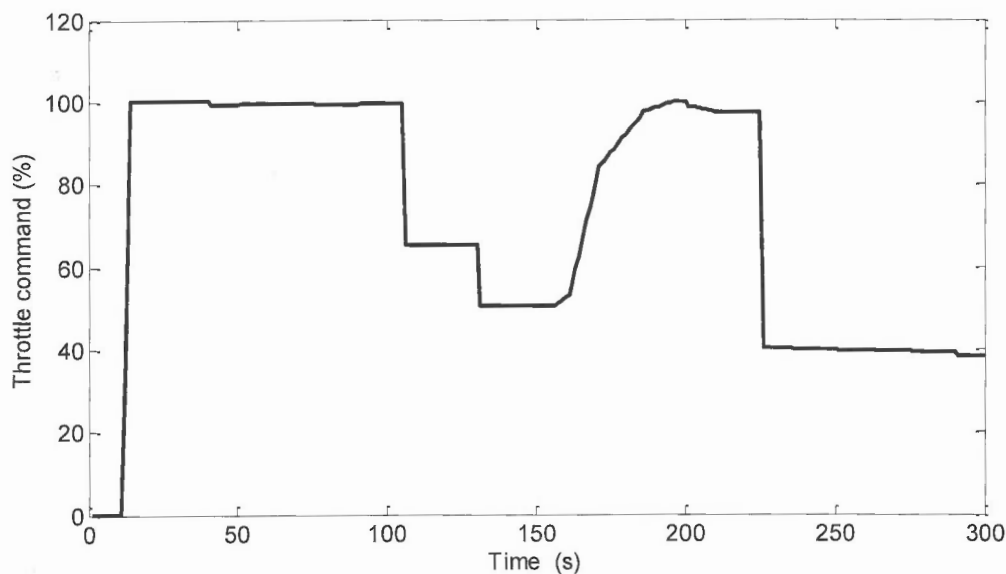


Figure 8-3. Throttle commands during different flight phases, scenario I

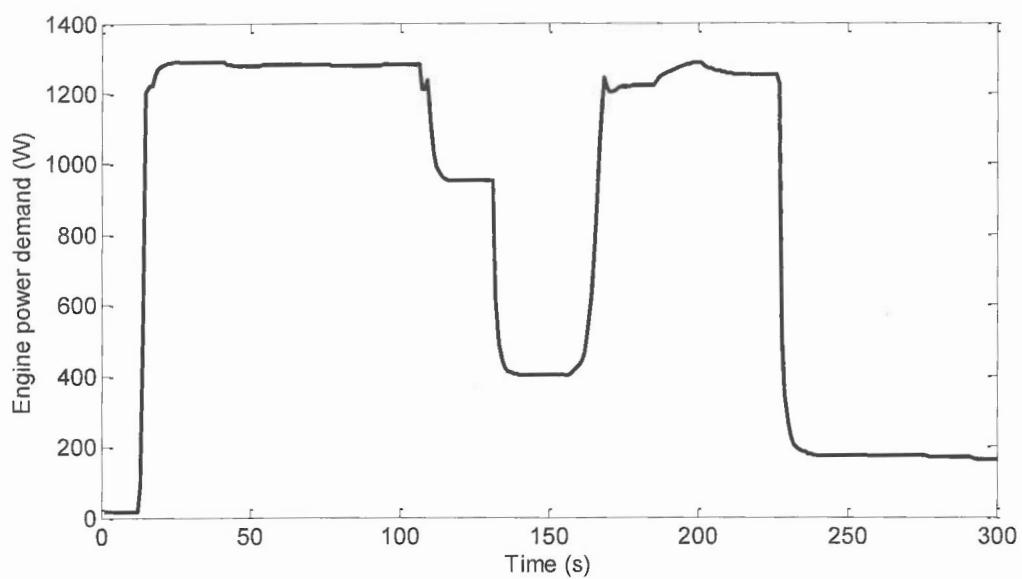


Figure 8-4. Engine power demand during different flight phases, scenario I

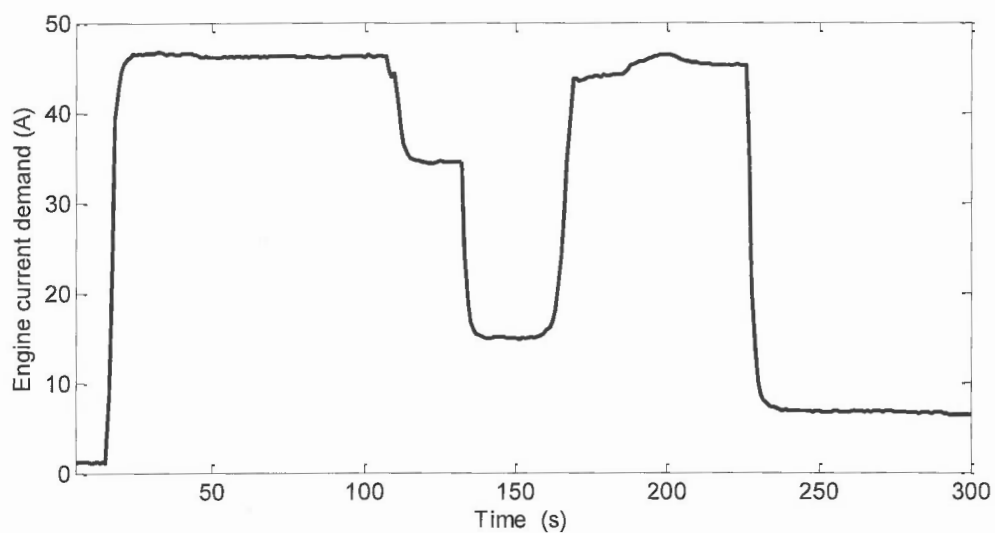


Figure 8-5. Engine current demand during different flight phases, scenario I

During take-off the throttle jumps from 0% to the maximum value of 100% in about 3 seconds with the power demand reaching 1285W as shown in Figures 8-3 and 8-4. The FC cannot supply all the power demanded during take-off and the FC output voltage decreases from 40.69V to 27.27V, while its stack current increases rapidly from 2.22A to 34.26A at the beginning of the transient interval. Then the voltage continues to fluctuate while the current gradually increases until it reaches 46A at 93 seconds, as illustrated in Figure 8-7. This is explained by the fact that the maximum power demand during the take-off stage is higher than the FC power transient and the extra power must be provided by the batteries. The battery current sharply increases from -1.674A to about 10A in line with throttle demands, see Figure 8-8. At the end of take-off the battery current tapers down to zero at 107 seconds and the FC current takes over, because the voltage from the FC side is now higher than the voltage from the battery side.

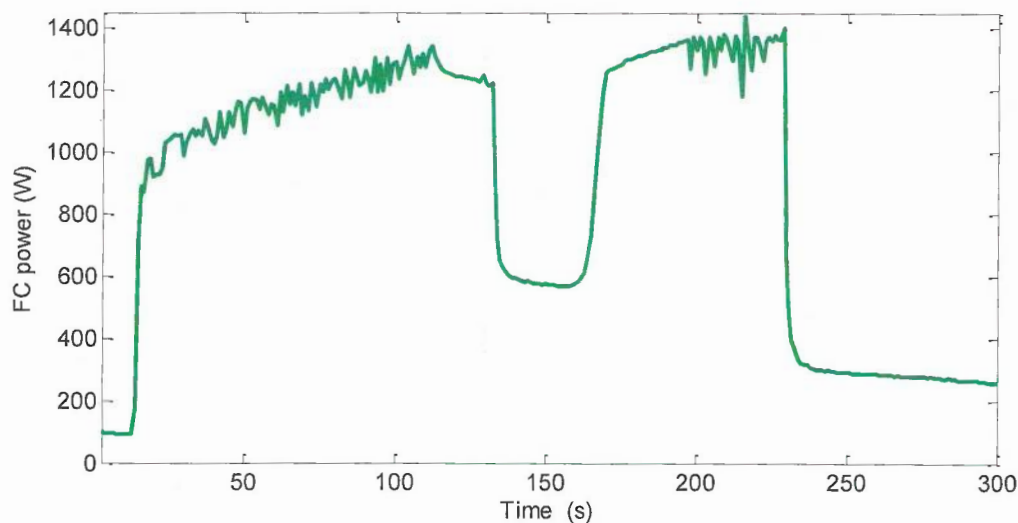


Figure 8-6. Power produced by the fuel cell during different flight phases, scenario I

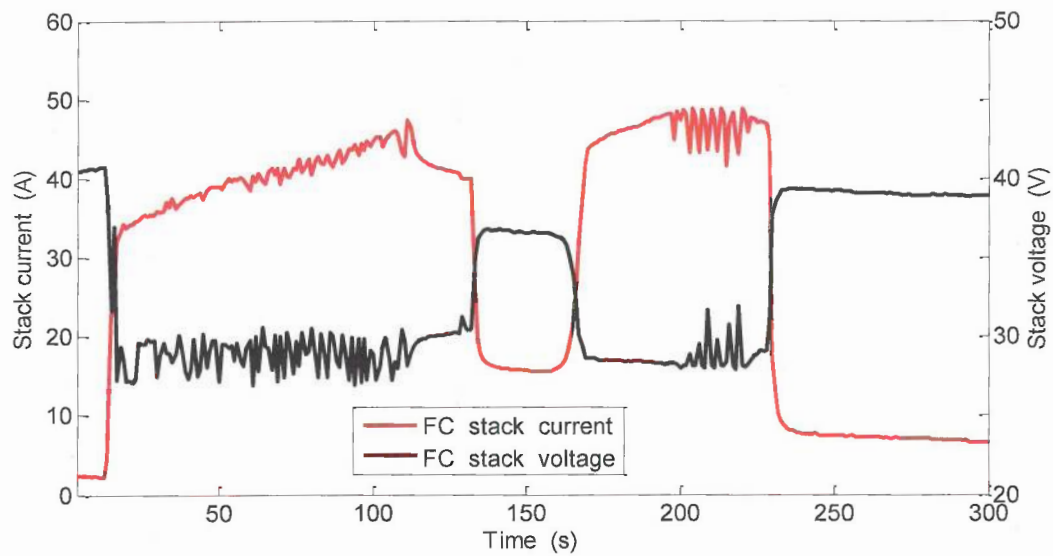


Figure 8-7. Fuel cell stack voltage and current during different flight phases, scenario I

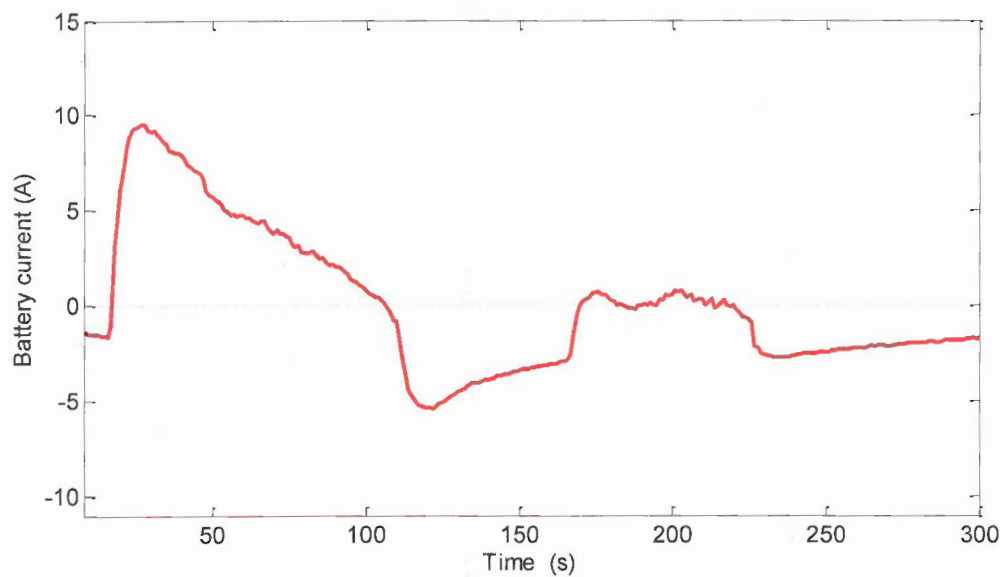


Figure 8-8. Battery current during different flight phases, scenario I

At 107 seconds the aircraft has completed take off and cruises for 25 seconds followed by descend for 26 seconds, during which the power demand drops to 402W. The FC can now provide power to both the engine and for charging the battery in nominal operating conditions. At 158 seconds, the aircraft now begins a slow climb that requires an engine power of 1285W which again demands current from both the FC and battery. However, this time the FC provides almost all the power, the stack current increases rapidly from 16.58A to 43A and stack voltage simultaneously drops

from 36V to 28.65V. The FC current continues to increase gradually to ~48A (1.36kW) and the stack voltage remains more or less constant at 28.65V. The FC no longer charges the battery and the battery current changes from -2.76A to 0.72A. Note very little power is taken from the batteries.

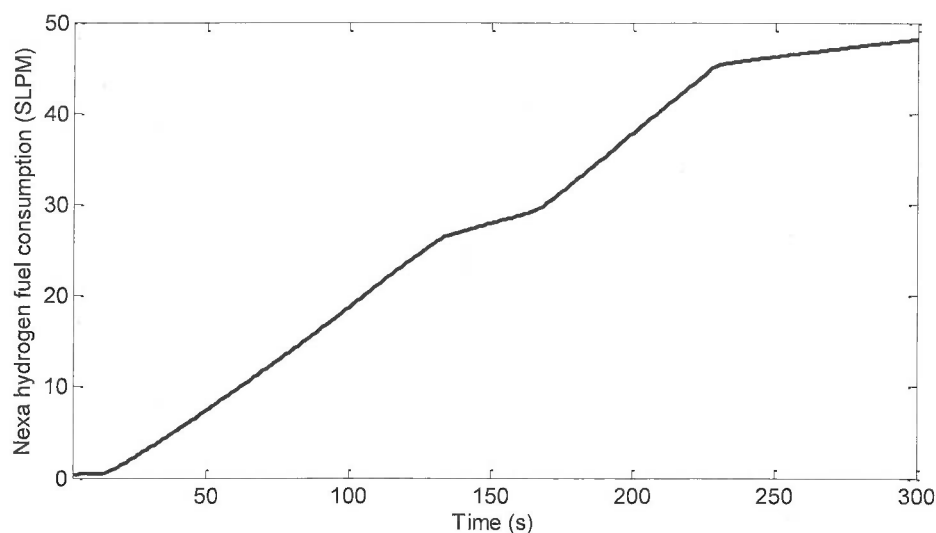


Figure 8-9. Nexa fuel consumption during different flight phases, scenario I

The slow climb ends at 225 seconds and the aircraft comes in to land. In this last phase of flight the power required is 172W and this is supplied entirely by the FC which provides a current 6A to the engine and about 2A to recharge the batteries. During the flight the batteries supply power only during periods of high transient power demand. Here the power is delivered to the electrical motor from both FC and battery or from only one of them depending entirely on the transient response of power demands without considering the power management between the two sources. The maximum Nexa FC efficiency is about 50% at part load and drop to 38% at full power (1.2kW) as shown in Figure 7-1. It can be seen that the FC is working at very low efficiencies when maximum power demands occur during take-off and climb. Figure 8-9 shows the Nexa PEMFC (1.2kW) had consumed 48.5 litres of hydrogen at the end of this flight scenario.

8.3 Case study II

The difference between this case study and the previous one is the details of the flight and the hybrid system configuration. In this scenario, the aircraft taxing in beginning of flight scenario then takes off at $t = 150$ seconds to climb to a height of 20m and performs a circuit with a radius of 1550m in cruise phase for 1237 seconds. It descends at $t = 1658$ seconds and then a slow climb was simulated before lands at $t = 2480$ seconds. Here the FC hybrid system consists of a 1.2kW PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter and electrical engine, see Figure 8-10. In the experiment same as in the previous case study, engine's load profile was implemented via a programmable electronic load. For the energy management, a fuzzy logic controller was implemented in the simulation and hardware-in-the-loop to manage the power between the two sources to meet the demand of the electric motor for each phase of flight. The controller has power demand and battery SoC (represented by battery voltage, if the total battery voltage was less than 30V the battery needed to be charged. Here 33V and 36V or more correspond to 50% and 100% SoC, respectively, see Section 5.2) as input variables and the output power of DC/DC bidirectional converter as the output variable, more details about controller implementation is presented in Chapter 7.

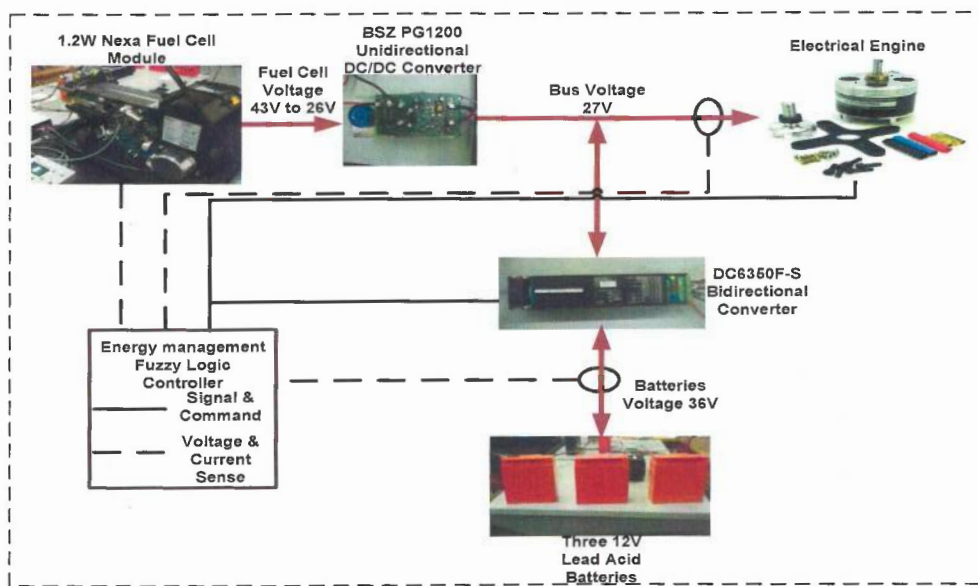


Figure 8-10. The schematic diagram of the hybrid system in case study II

Table 8-2 illustrates the maximum power demands for each stage of flight. The minimum power demand occurred when the aircraft taxi and land (24-26% throttle) while maximum power demand occurred during take-off and climb with 100% throttle. For the other two stages (cruising and descent) the required power is 470W and 215W, respectively.

Table 8-2. Power demands of flight phases for case study II

Throttle command (%)	Phases of flight	Require power (W)	Simulation time (s)
26%	taxi	78	0-150
100%	Take off	1285	150-421
53%	Cruising	470	421-1658
40%	Descent	215	1658-2124
100%	Climb	1285	2124-2480
24%	Landing	74	2480-2898

8.4 Results and discussion of the case study II

In case study II, the fuzzy logic controller was employed for power management of the FC/battery hybrid system to meet the electrical engine power demands of the PiperCub J3 aircraft. The FC/battery hybrid system was described in Section 6.2 of this thesis. The fuzzy logic controller was implemented in both simulation and hardware-in-the-loop. The input variables to the controller were power demand and battery SoC (represented by battery voltage); the output power of DC/DC bidirectional converter was the output variable.

The throttle commands plot for this scenario is shown in Figure 8-11, the corresponding current profile load and power demand of the engine are shown in Figures 8-12 and 8-13, respectively. For the first 150 seconds, the aircraft is taxiing and the engine requires only 79W which draws 2.8A, and that is supplied entirely from the FC, see Figures 8-12, 8-13 and 8-14.

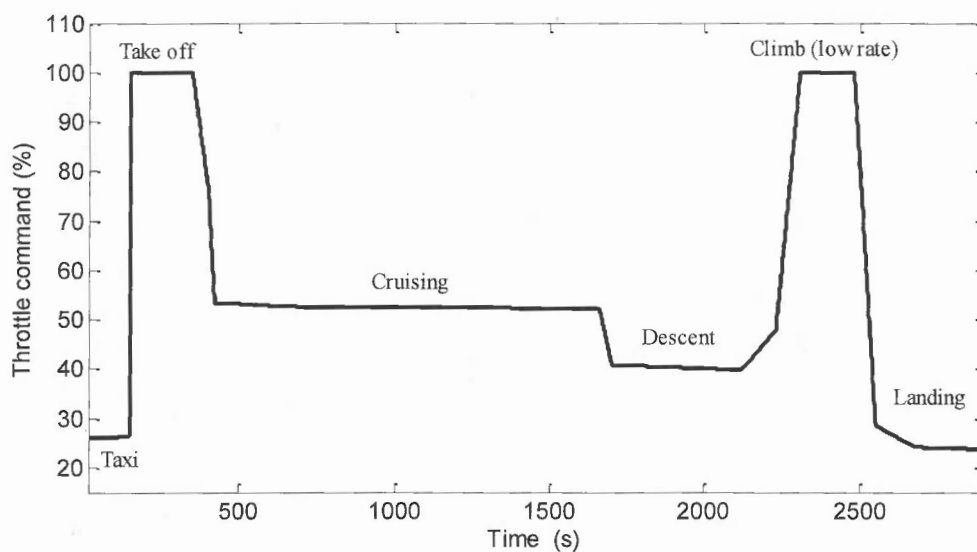


Figure 8-11. Throttle commands during different flight phases, scenario II

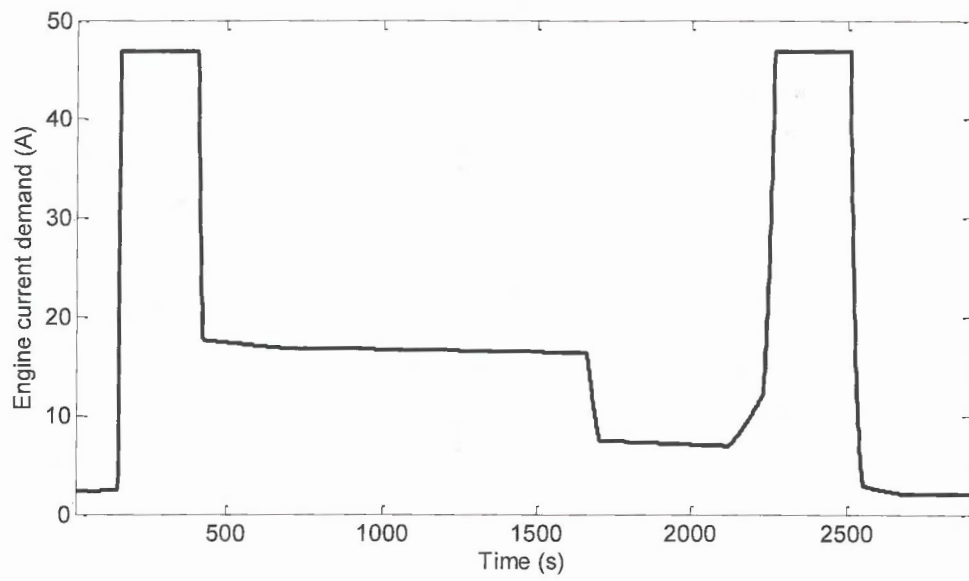


Figure 8-12. Engine current demand during different flight phases, scenario II

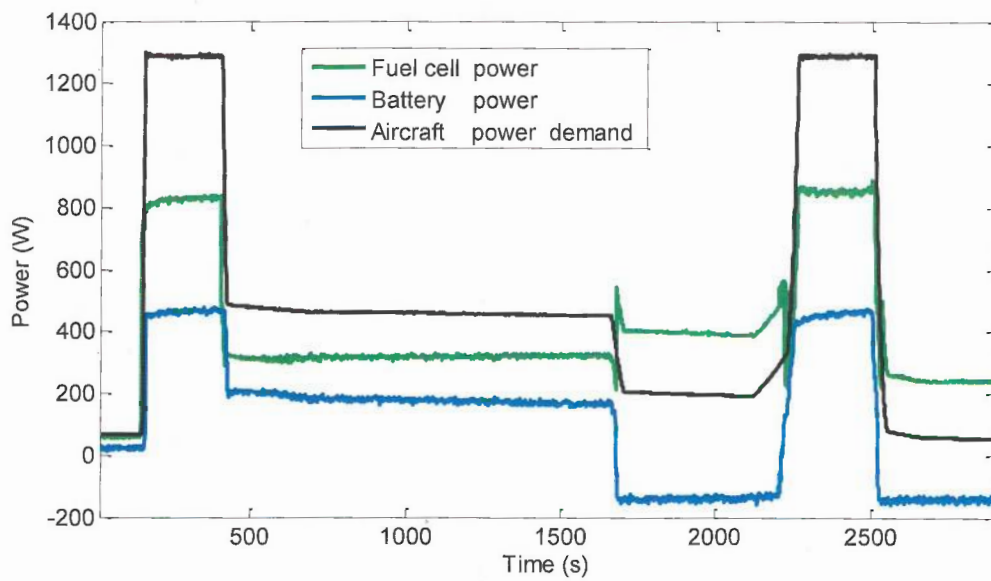


Figure 8-13. Engine power demand, FC power and battery power during different flight phases, scenario II

During take-off the throttle jumps from 26% to the maximum value of 100% in about 3 seconds with the corresponding total power demand reading 1285W and current 46.5A. The duration of this demand is 271 seconds, from 150 to 421 seconds, see Figures 8-11, 8-12 and 8-13. For this stage the FC stack current increased from 2.3A to 27.7A (see Figure 8-14), while stack voltage drops from 41V to 29V to supply 827W as shown in Figure 8-15. Instantaneously the fuzzy logic controller sent a signal to the bidirectional converter to make up the power shortfall from the batteries and battery current increased sharply from about 0A to 15A in line with the throttle changes, see Figure 8-16. The corresponding battery voltage decreased as shown in Figure 8-17. The power sharing during this take-off stage as result made the PEMFC operate at its optimum efficiency point while delivering power to the electric engine and acting as the main power source.

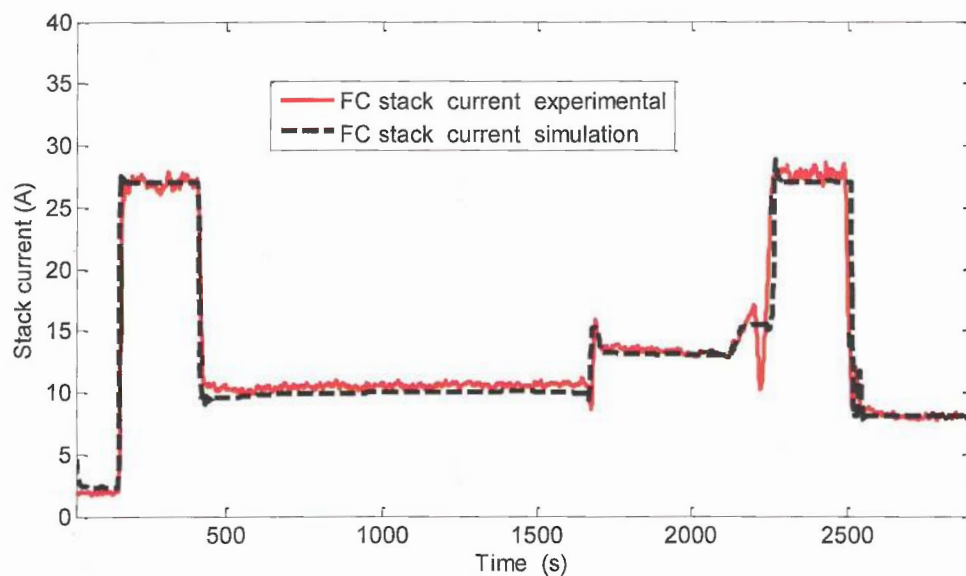


Figure 8-14. Fuel cell stack current during different flight phases, scenario II

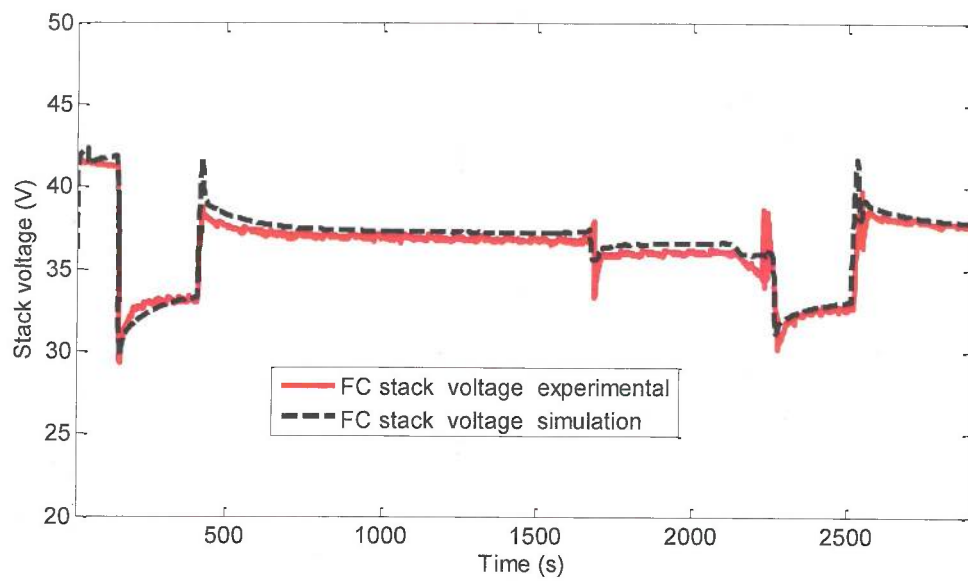


Figure 8-15. Fuel cell stack voltage during different flight phases, scenario II

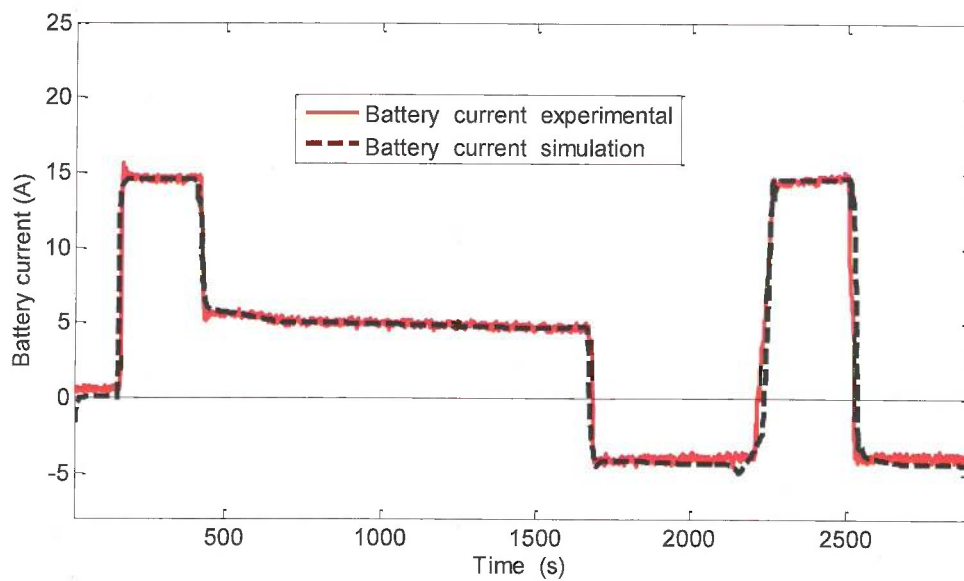


Figure 8-16. Battery current during different flight phases, scenario II

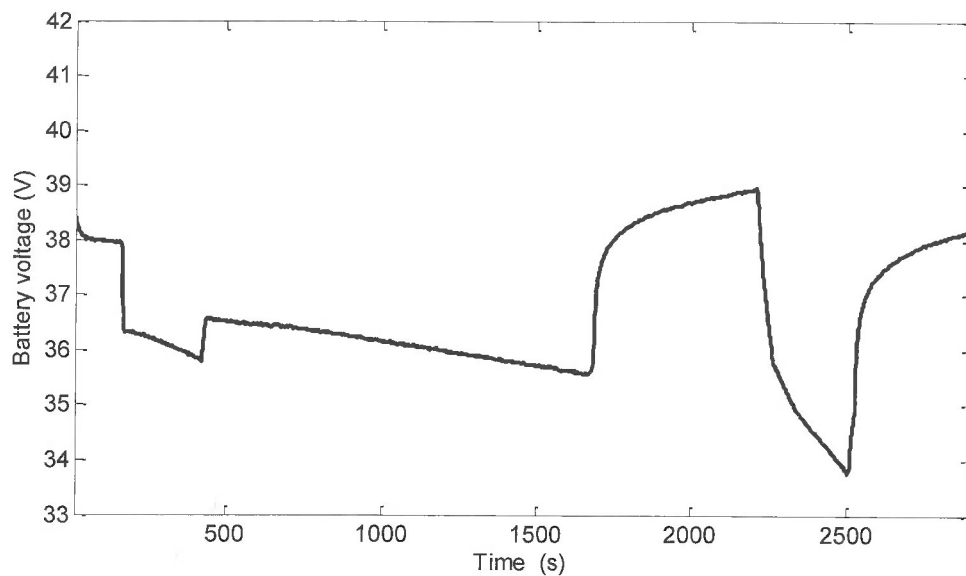


Figure 8-17. Battery voltage during different flight phases, scenario II

At 421 seconds the aircraft starts cruising and this continues until 1658 seconds (duration of 1237 seconds). During cruising the aircraft requires 460W, the FC supplies 318W and the batteries supply 142W (please note that depends on their SoC). At 1658 seconds the aircraft begins a shallow descent which lasts 466 seconds. Figure 8-13 shows the overshoot at $t = 1658$ seconds and undershoot at $t = 2124$ seconds in FC power, current and voltage response. These due to the bidirectional converter switch to charge and discharge the battery, respectively. During the descent stage the power demand drops to 200W and the FC can now provide power to both the engine and to charge the battery in nominal operating conditions with maximum efficiency (50%) as shown in Figure 8-18. The negative values of battery current in Figure 8-16 correspond to the battery being charged. Battery voltage is given in Figure 8-17.

At the end of the descent (2124 seconds) the aircraft began a slow climb which lasted for 356 seconds during which the engine required a total of 1285W from the FC and the battery combined. This climb is simulated in the case study to emulate real flight go around scenarios. The battery current increased to 14.8A and the battery voltage decreased. After the slow climb came the last phase of the flight is landing. The required power was 74W, the FC supplied 245W and the additional power was used to charge up the batteries with a current of -4.3A, see Figure 8-16. The results are from the experiment and simulation show good agreement. Figure 8-19 shows how

much hydrogen the FC needed to satisfy the power requirements of the aircraft during the flight: take-off, climb, cruise, descent and landing. The Nexa PEMFC (1.2kW) had consumed 378 litres of hydrogen at the end of the flight scenario.

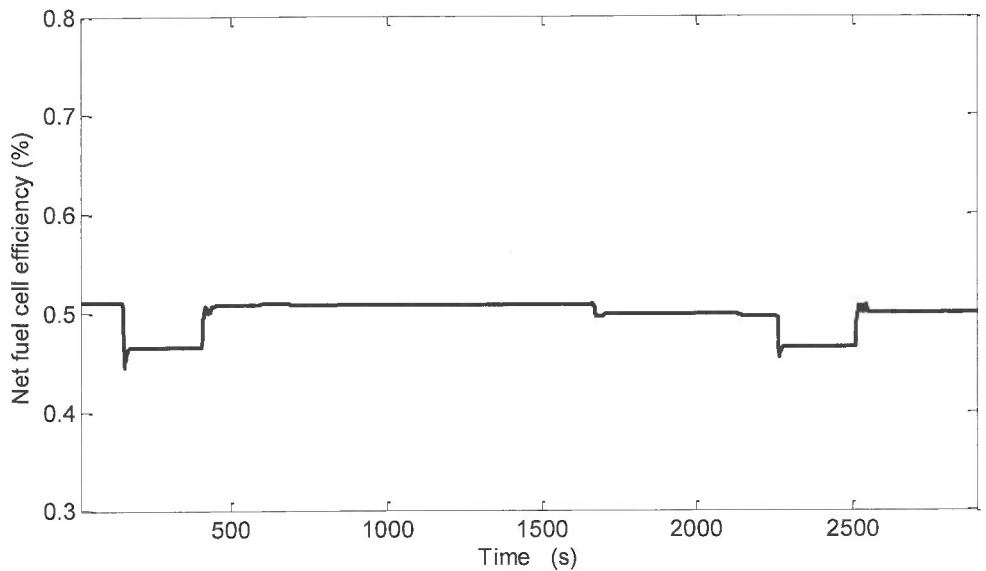


Figure 8-18. Fuel cell efficiency during different flight phases, scenario II

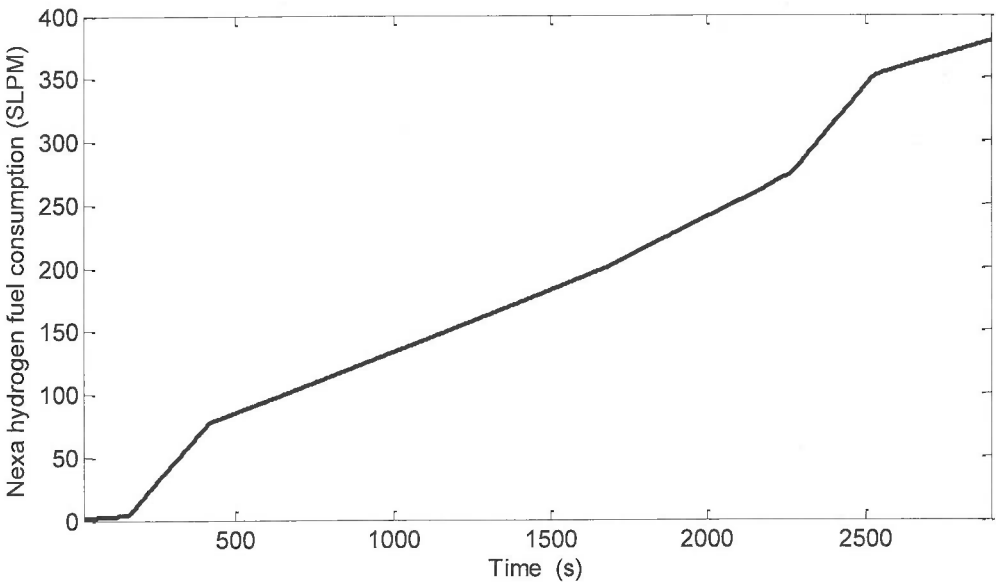


Figure 8-19. Nexa fuel consumption during different flight phases, scenario II

8.5 Worst case scenario in case study II: battery low state of charge

In the hybrid system, there are three 12V lead acid batteries connected in series to give 36V. One input to the fuzzy logic controller is the battery state of charge (SoC) represented by the battery voltage. The fuzzy logic control system included the condition that if the total battery voltage was less than 30V the battery needed to be charged. Here 33V and 36V (or more) correspond to 50% and 100% SoC, respectively.

After completing the test of scenario II, the batteries had been operating for a long time. The test was then repeated without charging the battery to investigate fuzzy logic controller performance during the worst case scenario when the battery cannot supply power to assist the FC. For the first 150 seconds, the aircraft is taxiing and the engine requires 2.8A, during this time the FC provides current to both the engine and for charging the battery in nominal operating conditions as shown in Figure 8-20. Once again the negative current values in Figure 8-21 correspond to the battery being charged, and also from Figure 8-21 it can be seen that during this charging period battery voltage is 38.5V.

During take-off the current demand reading is 46.5A, see Figure 8-20. In this stage the FC stack current increase from 9.4A to 28A. Instantaneously the fuzzy logic controller sent signal to the bidirectional converter to make up the current shortage from the batteries. The battery's current sharply increases from about -4.64A to 16A in line with throttle changes, while the battery voltage drops from 38.9 to 35V in one step and decreases gradually to about 30.8V before the take-off stage finishes, see Figure 8-21. Due to low battery voltage the controller takes less current from the battery and the FC provides more current.

At 421 seconds the aircraft starts cruising and typically requires 16.8A on average in phase of the flight. Initially the FC supplies 10.12A and takes 6.8A from the batteries, but after about a minute of cruising, at 485 seconds, the battery current started to decrease and gradually faded until it reached 1A. Simultaneously battery voltage decrease from 32.44V to 30.6V. The FC had to supply the current shortfall from the

battery and in Figure 8-20 the battery and FC stack currents can be seen moving in opposite directions.

After cruising for 1658 seconds during which the FC stack was supplying an increasing current there followed by descend for 466 seconds, during which the current demand dropped to 7.6A. The battery voltage was low (30V or less) and the controller switched the DC/DC converter to charging mode. The FC then provides current to both the engine and for charging the battery with maximum efficiency, see Figures 8-20 and 8-21.

At 2124 seconds a slow climb was commenced that required 46A from both FC and battery to meet the engine power demand. The battery current increased to 15A. The battery voltage remains at about 37V until about 2179 seconds when it starts to drop. At 2300 seconds the battery voltage reaches 30.32V and then drops slowly to 29.82V. This drives the controller to take less and less current from the battery, see Figure 8-21 and FC current takes over, see figure 8-20. In the last phase of the flight the required power is 2.7A, The FC supplies this and the additional current is used to charge up the batteries again, see Figure 8-21.

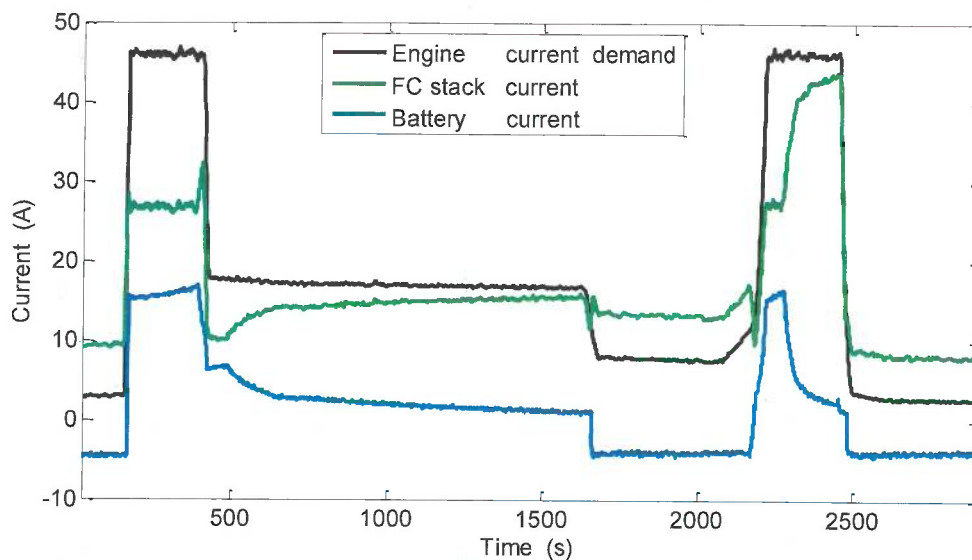


Figure 8-20. Engine current demand, FC current and battery current during different flight phases, scenario II with low SoC

The flight successfully completed in the same time as previously. But the FC was working at very low efficiency when maximum power demands occurred during the end of the take-off and climb (about 40%). The results show that fuzzy logic controller performance could deal with the worst case scenario when the battery cannot always supply power to assist the FC. Figure 8-22 shows how much hydrogen the FC needed to satisfy the power requirements of the aircraft during the flight: take-off, climb, cruise, descent and landing. The Nexa PEMFC (1.2kW) had consumed 473 litres of hydrogen at the end of the flight scenario. It can be seen the FC consumed 94 litres more than the previous flight because of low battery SoC while the FC operated at low efficiency.

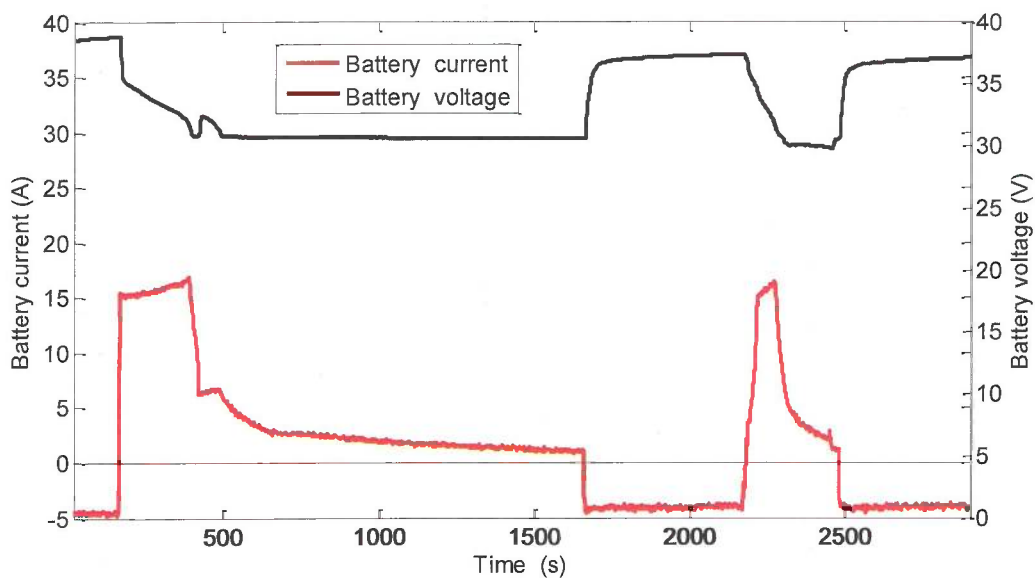


Figure 8-21. Battery voltage and current during different flight phases, scenario II with low SoC

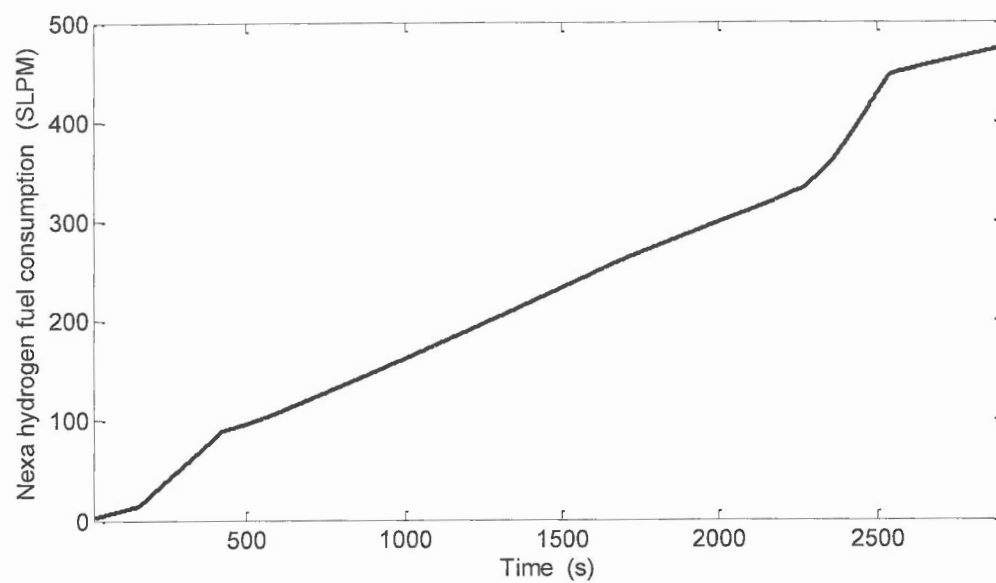


Figure 8-22. Nexa fuel consumption during different flight phases, scenario II with low SoC

8.6 Chapter summary

Two flight test scenarios were presented in this chapter, including also the worst case scenario in which the battery could not supply the required power to assist the FC. The case studies verified that the fuel cell could be used in a hybrid system configuration as main power source for a small aircraft.

In case study I, the hybrid system consisted of a 1.2kW PEMFC, a unidirectional step-down DC converter and two 12V batteries driving an electrical engine. It satisfied desired power requirements for different flight phases without controller to manage the power flow between the two sources. However the FC was operating at very low efficiency (38%) and consumed 48.5 litres of hydrogen. In case study II, the hybrid system consists of a 1.2kW PEMFC, three 12V batteries, a unidirectional step-down DC converter, a bidirectional DC converter and the electrical engine. Feed-forward fuzzy logic controller was used in this case study to manage the power flow between the two sources. FC operated at higher efficiencies (50%) and consumed 378 litres of hydrogen to meet the desired power requirements for different flight phases (taxi, take-off, climb, cruising, descent and landing). Based on results of the worst case scenario in case study II, we conclude that combination of FLC and fully charge battery resulted in the highest efficiency, saving 94 litres of hydrogen (about 25% higher efficiency).

9 Conclusions and Recommendation

This thesis has presented an investigation into the feasibility of using an electric hybrid system that consists of a 1.2kW Nexa PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter and a bidirectional DC/DC converter to power a small aircraft. The main focus of the thesis was to develop a simulation model of the FC hybrid system in MATLAB/Simulink environment and implementing advanced control strategies in both simulation and hardware-in-the-loop to manage and optimise the power between the two sources.

The dynamic model in this research study was based on a 1.2kW PEMFC. The model is semi-empirical model derived from theory and experimental results. The experimental data obtained from a Nexa power module were used as inputs to the simulation model; namely, air pump voltage, fan voltage, ambient temperature, anode purge valve status and current demand. The model was validated with the experimental data acquired from the Nexa PEMFC, the results showed good agreement. The model for BSZ PG 1200 DC unidirectional convertor was formed through a series of lookup tables. Data was acquired directly from the hardware and then interpolated to populate the tables. The bidirectional buck-boost DC/DC converter circuit model was based on the half H-bridge topology. The circuit has two sets of terminals, high voltage terminal V_{High} and a low voltage terminal V_{Low} . If a voltage source is applied to the high voltage terminal, then the converter will act as a buck or step-down converter. On the contrary the converter shall act as a boost or step-up if the voltage is applied on the low voltage terminal. The standard battery block in Simulink SimPowerSystems® toolbox was used to simulate the 21V lead acid battery. As for the electric engine model, the Dualsky XM5050CA DC engine variant was selected for the PiperCub J3 aircraft. The engine was tested under different throttle commands inputs and the recorded outputs were used to formulate the model. It was found that maximum engine power required 1290 Watts at 47.4A to generate the maximum RPM of 5460.

Experimental investigation of the dynamic performance and transient responses of Nexa (1.2kW) PEMFC under various load changes were presented. The dynamic tests

were carried out and separated into different stages: start-up, step-up load, irregular load variation and shut-down. The highest transient response of the Nexa FC during the step-up load current was tested. During the test, the load current increased at 12 seconds and 265 seconds in one jump from about 5A to 35A. Over the period of the test the stack current took one second to increase in steps from 5A to 35.9A and from 5A to 35.9A following the load, respectively. The stack voltage dropped from 40V to 29V and from 39.9V to 29V with small undershoots and took about 50 seconds to return operating at constant voltage (approximately at 31V). If the load current is increased from 5A to just over 35A in one step, then the Nexa FC will shut-down.

Power Management:

Simulations were first conceived with the purpose of studying hybrid system behaviour when subjected to test cycles purposely designed for load variation. A PI controller was designed and implemented in the simulation model. Its aim was to control the system and maintain the fuel cell operating under optimal condition. The controller performance was satisfactory exhibiting a 25 seconds settling time. During hardware-in-the-loop testing a differential component was found to be necessary to maintain performance. Therefore, a PID controller was designed and implemented in hardware-in-the-loop to control the battery current via the bidirectional DC/DC converter. When the load current was a step changed between 5A and 35A. It was observed that the current drawn from the FC followed the load current, while the battery current showed a considerable delay (10 seconds). This was due to the controller's integral component which introduced a lag into the closed loop system, but could not be removed as it was necessary for minimising steady-state error.

The delay in supplying power to the aircraft is not acceptable. The PID controller was therefore replaced by a fuzzy logic controller (FLC). The FLC was implemented in both simulation and hardware-in-the-loop to manage the power between two sources by controlling bidirectional DC/DC converter (in current control mode). Depending on the power demand, the FLC determined how much current to be supplied to or from the batteries. This controller has two input variables and one output variable. The input variables are the power demand and the battery SoC represented by the battery voltage. The output variable is the bidirectional DC/DC converter's output

power. In tests where FL was implemented, the load current was stepped up from 0A to 30A. The results indicated that the batteries current adheres to the transient response without any delay to supply about 10A; the FC optimum was reached at 20A.

Case studies:

In case study I the flight scenario was set up to investigate the feasibility of using the Nexa FC/battery hybrid system to satisfy the power requirements of the Piper Cub J3 aircraft during all phases of flights including take-off, climb, cruise, descent and landing. In this case, the electric hybrid system configuration consisted of a 1.2kW PEMFC, a unidirectional step-down DC/DC converter and two 12V batteries driving an electrical engine (see Figure 8-1). The converter was connected such that it maintains the output voltage from the FC at 27V. The rechargeable batteries at the converter output guarantee a stable and dynamic operation of the hybrid system. During the experiment, the engine load profile was implemented via a programmable electronic load. Power was delivered to the electrical engine without a controller to manage it. The results showed that the battery provided power only during take-off when the throttle jumps from 0% to the maximum value of 100% in about 3 seconds. The battery current sharply increased from -1.674 to about 10A in line with throttle changes and then at the end of the take-off stage the battery current tapered down to zero. Since the FC was worked at very low efficiency (38%) maximum power demands occurred during take-off and climb as well. The Nexa FC consumed 48.5 litres of hydrogen at the end of the flight scenario to satisfy power requirements for different flight phases.

The difference between the case study II and the first were the details of the flight and the hybrid system configuration. Here, the FC hybrid system consists of a 1.2kW PEMFC, three 12V lead acid batteries, a unidirectional step-down DC/DC converter, a bidirectional DC/DC converter and electrical engine (see Figure 49). During the experiment, engine load profile was implemented via a programmable electronic load. Power management between two sources was achieved by implementing the FL controller in both simulation and hardware-in-the-loop to manage the power flow between two sources. During the flight scenario, the FC tended to operate at high

efficiency (50%) and both sources supplied the desired power for different phases of flight (taxi, take-off, cruising, descent, climb and landing). The Nexa PEMFC (1.2kW) had consumed 378 litres of hydrogen at the end of the flight scenario. The experimental results were used to validate simulation models. The comparison between them showed good agreement.

Finally, a worst case scenario was investigated. In this instance the battery cannot supply the required power to assist the FC. The flight was successfully completed in the same manner as Case study II. The FC was working at very low efficiency and consumed more hydrogen when maximum power demands occurred during the end of the take-off and climb phases. The Nexa PEMFC (1.2kW) had consumed 473 litres of hydrogen at the end of the flight scenario. It can be seen that the FC consumed 94 litres more than the previous flight because of low battery SoC and in this case the FC operated at low efficiency. Also, the results showed that FL controller performance was dealing with the worst case scenario when the battery cannot supply power to assist the FC. So the combination of FLC and fully charge battery resulted in the highest efficiency, saving 94 litres of hydrogen (about 25% higher efficiency).

Recommendations:

The FC/battery electric hybrid system designed in this thesis is based on existing technology and most of the components have been designed for integration into a wide variety of stationary and automotive power generation applications. Unlike aircraft design, in these applications weight is not a critical parameter. It would be useful to study weight saving methods for designing and manufacturing hybrid system components specifically for aviation application.

The problem of hydrogen storage has not been considered in this thesis. It would be useful for aviation application to consider the issues related to various types of hydrogen storage, such as gas tank, temperatures and pressures, or metal hydrides within the limited space available in on airframe.

Although a complete 6 Degree of Freedom aircraft model was used in this research, it would be more realistic if power requirements from the full flight control system (command stability augmentation and autopilots) are studied for manoeuvre and turbulence cases. Linking the existing simulation model to a higher level energy management system that takes into account external factors e.g. wind speeds, wind direction and optimising trajectory and path planning may help in the design integration and optimisation of FC hybrid power systems on board on aircraft.

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APPENDICES

1 Appendix A

A.1 Calculation of change in Molar Gibbs free energy for hydrogen fuel cell

We define the Gibbs function of a system, G , in terms of the enthalpy, H , and entropy, S :

$$G = H - TS \quad (A1.1)$$

Where T is the absolute temperature, K . From this we can say the molar Gibbs energy of formation, $\bar{g}_f$, is directly related to the molar enthalpy of formation, $\bar{h}_f$, and the molar entropy, $\bar{S}$:

$$\bar{g}_f = \bar{h}_f - T\bar{S} \quad (A1.2)$$

Given that in a fuel cell, the temperature is constant we can say that the change in energy is:

$$\Delta\bar{g}_f = \Delta\bar{h}_f - T\Delta\bar{S} \quad (A1.3)$$

Where $\Delta\bar{h}_f$ is the difference between molar enthalpy of formation, $\bar{h}_f$, of the products and reactants.

To determine $\Delta\bar{g}_f$ for the hydrogen reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$, will require a number of steps. First:

$$\Delta\bar{h}_f = (\bar{h}_f)_{H_2O} - (\bar{h}_f)_{H_2} - \frac{1}{2}(\bar{h}_f)_{O_2} \quad (A1.4)$$

Similarly, $\Delta\bar{S}$ is the difference between molar entropy, $\bar{S}$, of products and reactants.

So in the hydrogen reaction:

$$\Delta\bar{S} = (\bar{S})_{H_2O} - (\bar{S})_{H_2} - \frac{1}{2}(\bar{S})_{O_2} \quad (A1.5)$$

The molar enthalpy of formation at temperature T is given by:

$$\bar{h}_T = \bar{h}_{298.15} + \int_{298.15}^T \bar{c}_P dT \quad (\text{A1.6})$$

The molar entropy is given by

$$\bar{S}_T = \bar{S}_{298.15} + \int_{298.15}^T \frac{1}{T} \bar{c}_P dT \quad (\text{A1.7})$$

The values of $\bar{h}_f$ and $\bar{S}$ vary with temperature according to Equations (A1.6) and (A1.7). The subscript 298.15 on $\bar{h}$ and $\bar{S}$ is the initial standard temperature, and $\bar{c}_P$ is the molar heat capacity at constant pressure which must be known.

Table A1.1 gives the values for the molar entropy and enthalpy of formation at 298.15K at standard pressure (Keenan and Kaye, 1948).

Table A1.1 Values of $\bar{h}_f$ in J mol^{-1} and $\bar{S}$ in $\text{J mol}^{-1} \text{K}^{-1}$, at 298.15 K, for the hydrogen fuel cell

	$\bar{h}_f$	$\bar{S}$
$\text{H}_2\text{O (liquid)}$	-285,838	70.05
$\text{H}_2\text{O (steam)}$	-241,827	188.83
H_2	0	130.59
O_2	0	205.14

$\bar{c}_P$ varies with temperature, and empirical equations for $\bar{c}_P$ are given in many thermodynamics textbooks (Van Wylen, 1986). Equations (A1.8) for steam, (A1.9) for hydrogen and (A1.10) for oxygen are claimed as accurate to within 0.6% over the range 300 to 3500 K.

$$\bar{c}_P = 143.05 - 58.040T^{0.25} + 8.2751T^{0.5} - 0.036,989T \quad (\text{A1.8})$$

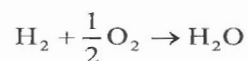
$$\bar{c}_P = 56.505 - 22,222.6T^{-0.75} + 116,500T^{-1} - 560,700T^{-1.5} \quad (\text{A1.9})$$

$$\bar{c}_P = 37.432 + 2.010,2 \cdot 10^{-5} T^{1.5} - 178,570T^{-1.5} + 2,368,800T^{-2} \quad (\text{A1.10})$$

$\bar{c}_P$ are in $\text{J g mole}^{-1}\text{K}$. These equations values for $\bar{c}_P$ can be substituted into Equations (A1.6) and (A1.7), giving functions that can be integrated and evaluated over the given temperature range to obtain values of $\bar{h}_f$ and $\bar{S}$ for steam, hydrogen

and oxygen. The values obtained can then be substituted into Equations (A1.4) and (A1.5) to give values for $\Delta \bar{h}_f$ and $\Delta \bar{S}$. These are then substituted into Equation (A1.3) to give $\Delta \bar{g}_f$ the change in the molar Gibbs free energy of formation. Sample values of $\Delta \bar{g}_f$ are given in Table A1.2.

Table A1.2. Change in molar Gibbs free energy of formation $\Delta \bar{g}_f$ for the reaction:



Temp °C	$\Delta \bar{h}_f$ kJ mol ⁻¹	$\Delta \bar{S}$ kJ mol ⁻¹	$\Delta \bar{g}_f$ kJ mol ⁻¹
100	-242.6	-0.046,6	-225.2
300	-244.5	-0.050,7	-215.4
500	-246.2	-0.053,3	-205
700	-247.6	-0.054,9	-194.2
900	-248.8	-0.056,1	-183.1

In the case of liquid water, standard values from Table A1.1 for $\bar{h}_f$ and $\bar{S}$ are used for 25 °C. At 80 °C, equations (A1.4) and (A1.5) are again used to find $\bar{h}_f$ and but over such a small temperature range we can assume that $\bar{c}_p$ is constant.

2 Appendix B

B.1 Buck PWM DC/DC converters

Figure B.1 shows a Buck Pulse Width Modulation (PWM) dc–dc converter circuit. A power MOSFET is used as the controllable switch, S , because of its high speed. A diode and transistor form a switching network which ‘chops’ the dc input voltage V_I which leads to the alternative name of the converter: ‘chopper’. The result is a reduced average voltage. The circuit also contains an inductor L , and a capacitor C in parallel with the resistor R_L which represents the DC load.

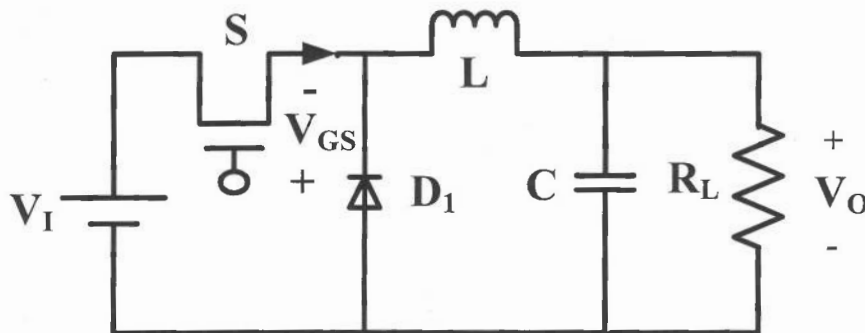


Figure B.1. PWM buck converter circuit

The PWM turns the switch S on and off at a switching frequency $f_s = 1/T$. The duty cycle, D , of the PWM drive signal applied to the gates of the MOSFET in the converter is the proportion of the total time that the switch is closed:

$$D = t_{on}/T = t_{on}/(t_{on} + t_{off})$$

Where T is the total time, t_{on} is the time the switch S is closed and t_{off} is the time the switch is open, see Figure B. 2.

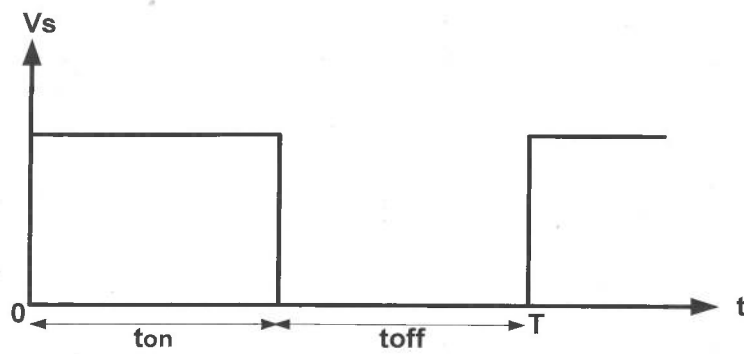
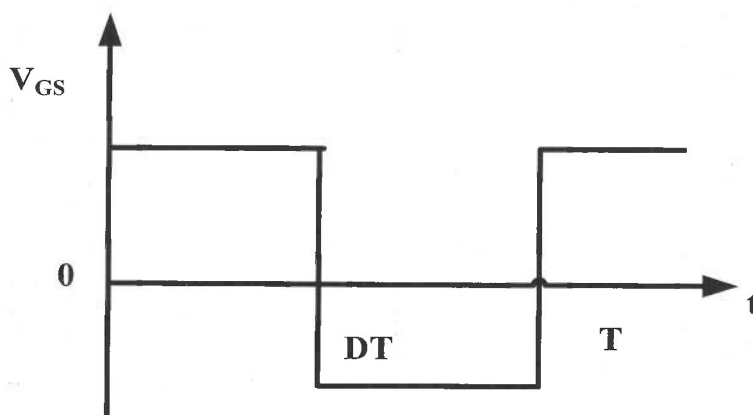


Figure B. 2. Switching Signal in one Duty cycle

The input voltage V_I is always greater than the output voltage V_O . The buck converter 'bucks' the voltage to a lower level. Because the gate of the MOSFET is not referenced to ground, it is difficult to drive the transistor. Depending on the waveform of the inductor current the converter can operate in a discontinuous conduction mode (DCM) where the inductor current flows for only part of the cycle, or a continuous conduction mode (CCM) where inductor current flows for the entire cycle. It is assumed that with DCM the current falls to zero and remains at zero for some time before starting to increase. The boundary between CCM and DCM is termed the critical mode.

The principle of operation of the converter is explained by reference to the idealized voltage and current waveforms shown in Figure B. 3.

The power switch S and the diode D_1 convert the dc input voltage V_I into a square wave at the input of the L - C - R_L circuit.



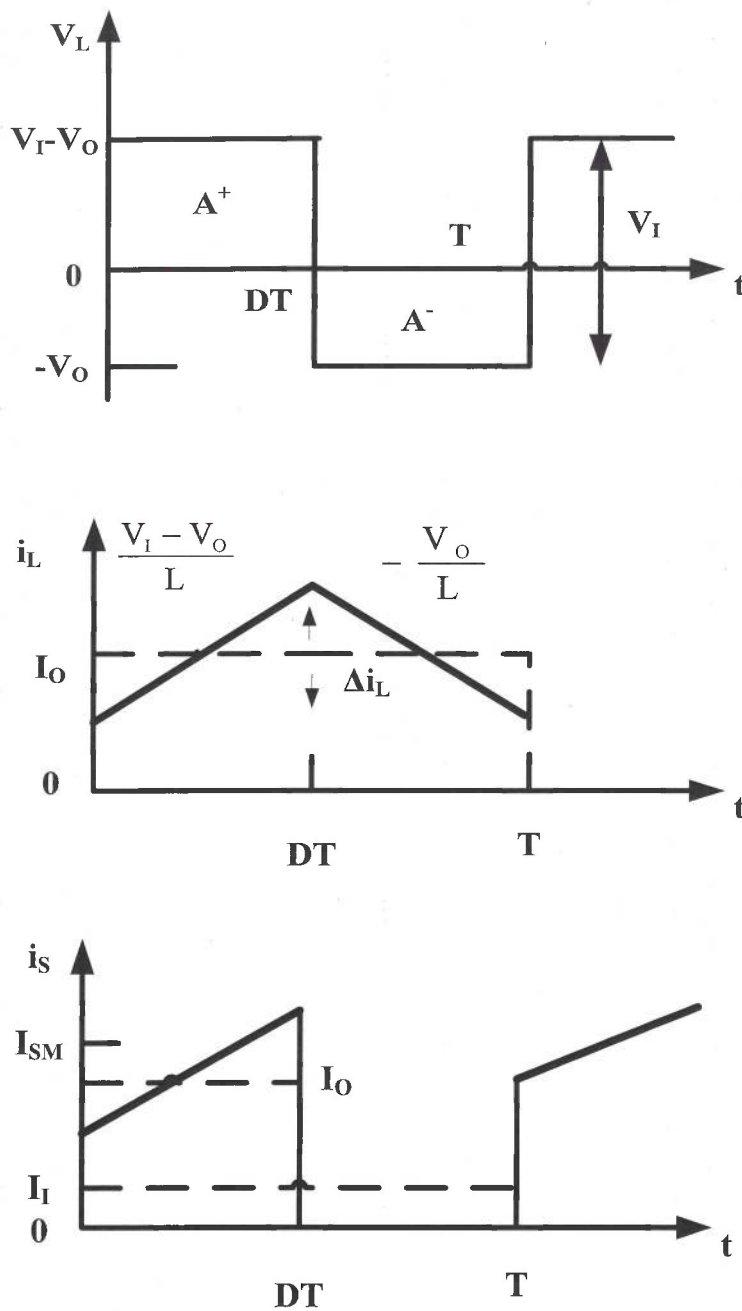


Figure B.3. Idealized current and voltage waveforms in buck converter for CCM

The L - C - R_L circuit converts the square wave into a low-ripple dc output voltage by acts as second order low pass filter. For steady state, the voltage across an ideal inductor L is zero, and the average output voltage V_O , across the load R_L , is by simple proportion equal to DV_I . This depends on the duty cycle D , and for the continuous mode of operation is almost independent of the load. If the dc input voltage V_I is increased, the duty cycle D is reduced so that the product DV_I remains constant.

Alternatively, if V_I is reduced, the duty cycle D is increased so that the average value of the PWM signal remains constant. In this way the amount of energy delivered from the input voltage source to the load can be controlled by varying the switch on-duty cycle D . Theoretically the output voltage V_O can range from 0 to V_I if the duty cycle D is varied from 0 to 100 %. In practice, however, to hold V_O at a fixed value the dc input voltage V_I is limited to a specified range.

B.1.1 Assumptions

Assumptions in the above analysis of the buck PWM converter shown in Figure B.1 are:

- The power MOSFET and the diode are assumed ideal switches.
- Switching losses may be neglected (diode capacitance, transistor output capacitance and lead inductances are assumed zero).
- All passive components are assumed frequency-independent, linear and time-invariant.
- The output impedance of the input voltage source is assumed zero for both ac and dc components.
- The converter is assumed to operate in the steady state.
- The time constants of reactive component are assumed to be much longer than the switching period $T=1/f_s$.

B.1.2 Time interval $0 < t \leq DT$

During the time interval $0 < t \leq DT$ shown in Figure B.3, the switch S is ON and the diode D_1 is OFF: an equivalent ideal circuit is shown in Figure B. 4.

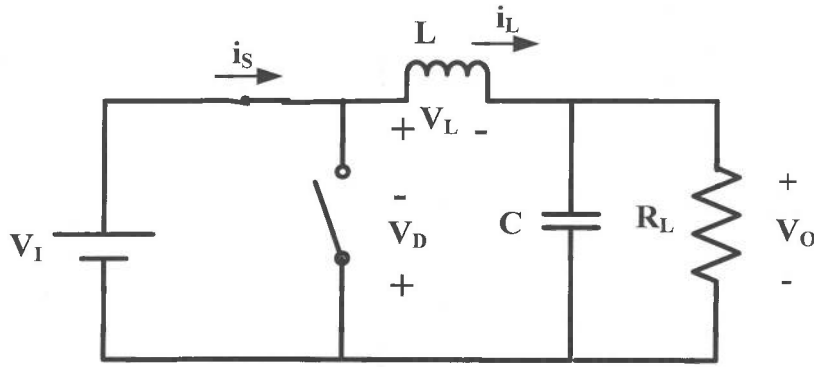


Figure B. 4. Equivalent circuit when the switch is ON and the diode is OFF for buck converter

When the switch is ON, the voltage across the diode is reverse biased and the diode current is taken as zero. The voltage across the inductor L is given by:

$$v_L = V_I - V_O = L \frac{di_L}{dt} \quad (\text{B1.1})$$

The rate of increase of current through the inductor is linear and equal to $(V_I - V_O)/L$. The same current flows through inductor and switch, so $i_S = i_L$. The current through the switch, S , and inductor, L , is:

$$i_S = i_L = \frac{1}{L} \int v_L dt + i_L(0) = \frac{V_I - V_O}{L} \int dt + i_L(0) = \frac{V_I - V_O}{L} t + i_L(0) \quad (\text{B1.2})$$

Where $i_L(0)$ is the initial current through the inductor, L . The peak inductor current is:

$$i_L(DT) = \frac{(V_I - V_O)DT}{L} + i_L(0) \quad (\text{B1.3})$$

The peak-to-peak ripple current of the inductor L will be:

$$\Delta i_L = i_L(DT) - i_L(0) = \frac{(V_I - V_O)DT}{L} = \frac{(V_I - V_O)D}{f_s L} = \frac{V_I D(1-D)}{f_s L} \quad (\text{B1.4})$$

The maximum value of the diode reverse voltage is V_I . The average value of the inductor current is equal to the dc output current I_O . Hence, one arrives at the maximum switch current, I_{SM} :

$$I_{SM} = I_O + \frac{\Delta i_L}{2} \quad (\text{B1.5})$$

The increase in the magnetic energy stored in the inductor, L , over time $0 - DT$ is:

$$\Delta W_{L(m)} = \frac{1}{2} L [i_L^2(DT) - i_L^2(0)] \quad (\text{B1.6})$$

B.1.3 Time interval $DT < t \leq T$

For the time interval $DT < t \leq T$, switch S is OFF and the diode is ON. Figure B.5 shows an equivalent ideal circuit. $i_L(DT)$ is non-zero when the switch turns off, the inductor current does not drop immediately to zero but decays with time. Thus the inductor may be considered to be a current source and forces the diode to turn on.

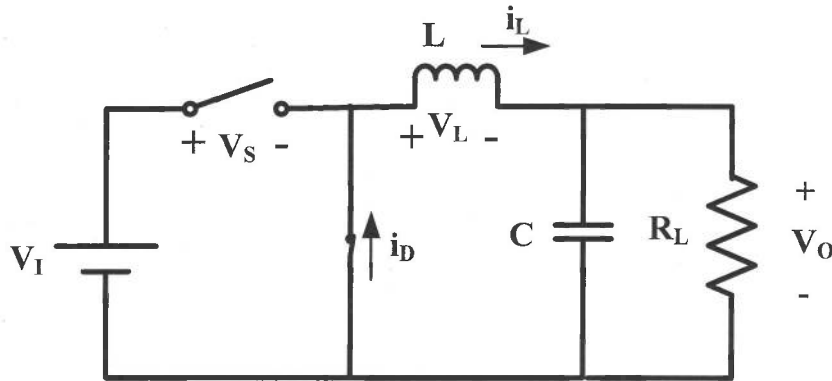


**Figure B. 5. Equivalent circuit when the switch is OFF and the diode is ON
for buck converter**

During this time interval, the input source V_I is disconnected from the circuit. The energy stored in the inductor L and capacitor C temporarily maintains the load voltage and current when the switch is OFF. In such a situation, where the diode voltage v_D is zero, the voltage across the inductor must be $-V_O$, and the inductor current decreases

linearly with gradient $-V_O/L$. At time $t = T$, the switch is ON again and the inductor current increases. PWM converters are operated at hard switching because the switch voltage waveform is rectangular and the transistor is turned on at a high voltage. The voltage across the inductor L is:

$$v_L = -V_O = L \frac{di_L}{dt} \quad (\text{B1.7})$$

The current through the diode and the inductor, L , can be found from:

$$i_D = i_L = \frac{1}{L} \int_{DT}^T v_L dt + i_L(DT) = -\frac{V_O}{L} \int_{DT}^T dt + i_L(DT) = -\frac{V_O}{L} (t - DT) + i_L(DT) \quad (\text{B1.8})$$

Where $i_L(DT)$ is the initial condition of the inductor at $t = DT$. The peak-to-peak ripple current of the inductor L is:

$$\Delta i_L = i_L(DT) - i_L(T) = \frac{V_O T(1-D)}{L} = \frac{V_O(1-D)}{f_s L} \quad (\text{B1.9})$$

In the continuous conduction mode the peak-to-peak value of the inductor current ripple Δi_L is independent of the load current I_O and depends only on the dc input voltage V_I and thereby on the duty cycle D . The shorter the duty cycle the more pronounced the inductor current ripple. From Equation (B1.9) it follows at once that the maximum value of the peak-to-peak inductor ripple current occurs at the minimum duty cycle, $D_{\min}$, as:

$$\Delta i_{L \max} = \frac{V_O(1-D_{\min})}{f_s L} \quad (\text{B1.10})$$

The maximum switch voltage V_{SM} and the switch voltage v_S are given in Equation (B1.11). The maximum switch and diode currents are given in Equation (B1.12).

$$v_S = V_{sm} = V_I \quad (\text{B1.11})$$

$$I_{DM} = I_{SM} = I_O + \frac{\Delta i_L}{2} \quad (\text{B1.12})$$

This time interval ends at $t = T$ when the switch is again turned on by the driver. The decrease in the magnetic energy stored in the inductor L during time interval $DT < t \leq T$ is given in Equation (B1.13). For steady-state operation, the increase in the magnetic energy $\Delta W_{L(in)}$ is equal to the decrease in the magnetic energy $\Delta W_{L(out)}$:

$$\Delta W_{L(out)} = \frac{1}{2} L [i_L^2(DT) - i_L^2(T)] \quad (\text{B1.13})$$

B.1.4 DC voltage transfer function of the buck converter for CCM

Faraday's well known law of electromagnetic induction states that the voltage generated in a conductor is proportional to the rate of change of flux through the conductor. Applying this to the inductor, L , for steady-state operation, when the boundary condition $i_L(0) = i_L(T)$ may be assumed, it follows at once that net voltage generated must be zero. Referring to Figure B1.3 that means the areas A^+ and A^- (the area enclosed by the positive part of the inductor voltage waveform A^+ and the area enclosed by the negative part of the inductor voltage waveform A^-) must be equal:

$$A^+ = \int_0^{DT} v_L dt \quad \text{and} \quad A^- = - \int_{DT}^T v_L dt \quad (\text{B1.14})$$

Referring to Figure B.3:

$$(V_I - V_O)DT = V_O(1-D)T \quad (\text{B1.15})$$

Which simplifies to:

$$V_O = DV_I \quad (\text{B1.16})$$

For a lossless converter, $V_I I_I = V_O I_O$. Hence, from Equation (B1.16), the dc voltage transfer function (or the voltage conversion ratio) of the lossless buck converter is given by:

$$M_{VDC} \equiv \frac{V_O}{V_I} = \frac{I_I}{I_O} = D \quad (\text{B1.17})$$

Where $0 \leq M_{VDC} \leq 1$. Note that the output voltage V_O depends only on the dc input voltage V_I and the duty cycle D , and is independent of R_L .

B.2 PWM boost converter for CCM

Figure B.6 shows the circuit for the PWM boost dc–dc converter. For steady-state conditions the output voltage V_O of the boost converter is always higher than the input voltage V_I . The converter consists of a power MOSFET, a diode D_1 , an inductor L , a filter capacitor C , and a load resistor R_L . S is switched on and off at frequency $f_s = 1/T$, and the ON ratio of the duty cycle, $D = t_{on}/T$, where t_{on} is the time interval for which switch S is ON.

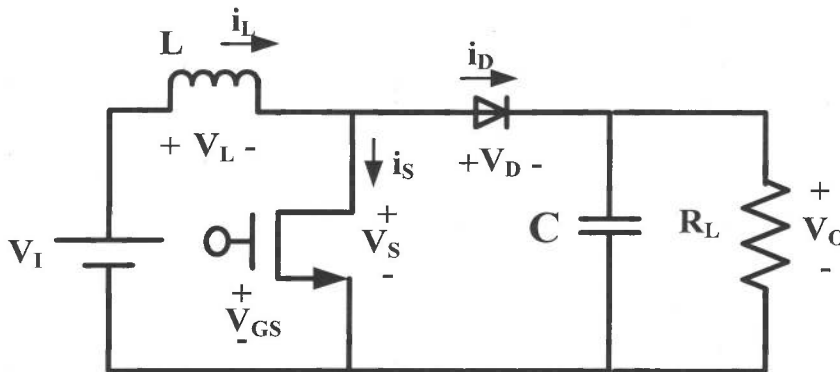
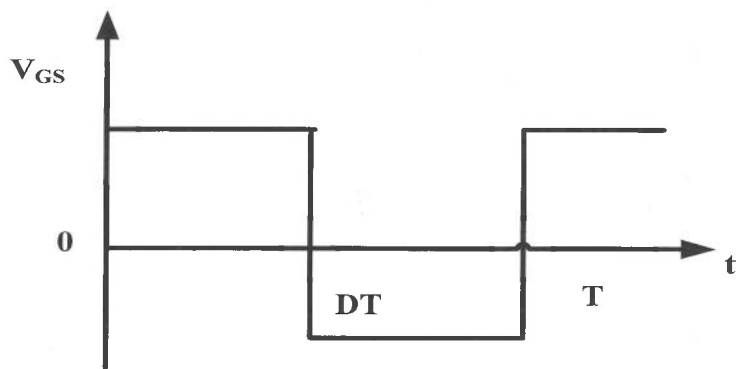
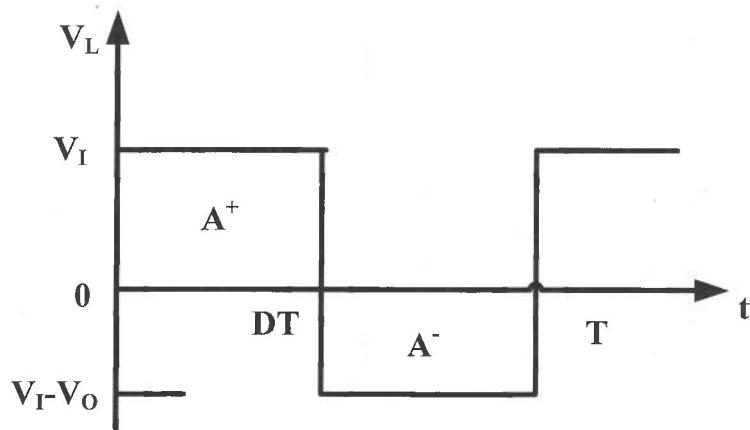
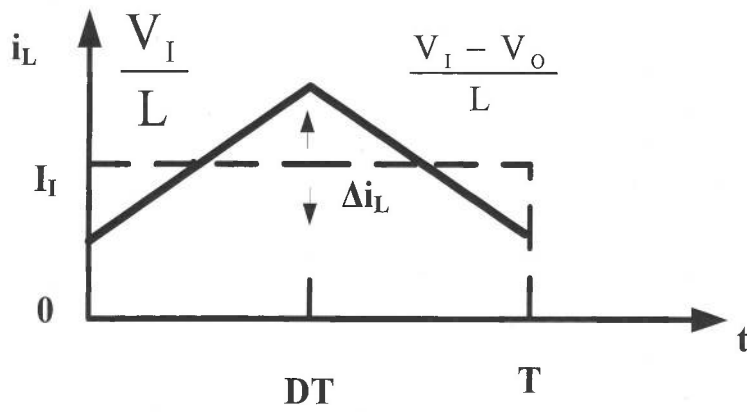


Figure B. 6. PWM boost converter circuit

The boost converter can operate in either DCM or CCM, depending on the waveform of the inductor current. In the DCM mode the boost converter requires that R_L is not open circuit ($R_L \neq \infty$) because in that case the capacitor would have no discharge path.

The continuous mode will be considered for the two conditions: switch S ON and diode OFF, and switch OFF and diode ON. Figure B.7 shows idealized current and voltage waveforms that help explain the principle of operation of the boost converter.



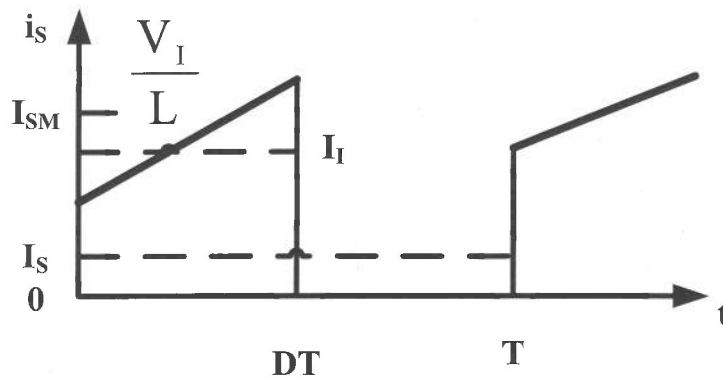


Figure B. 7. Idealized current and voltage waveforms for boost converter for CCM

The boost converter is not good at preventing hazardous transients and failures. A high positive voltage surge at the converter input and the diode D_1 will be ON for several cycles due to cycle skip. There will be a corresponding large current spike through the diode, which may destroy it. Similar problems exist at the initial turn ON/OFF the converter when the input voltage is high and the output voltage is initially zero and while the output voltage is lower than the input voltage until steady-state conditions are approached. One method used to protect the converter is to connect a diode between input source V_I (anode) and output filter capacitor C (cathode). Now if the input voltage is higher than the output voltage, the capacitor forms a peak rectifier and added diode, and the problem energy flows from the input of the converter to the output through the added diode. When the input voltage falls below the output voltage, the added diode is reverse biased and turned off, and the boost converter reverts to normal operation.

B.2.1 Assumptions

Assumptions made for the analysis of the boost PWM converter shown in Figure B.6 are:

- The power MOSFET and the diode are assumed ideal switches.
- Switching losses may be neglected (diode capacitance, transistor output capacitance and lead inductances are assumed zero).
- All passive components are assumed frequency-independent, linear and time-invariant.

- The output impedance of the input voltage source is assumed zero for both ac and dc components.

B.2.2 Time interval $0 < t \leq DT$

During the time interval $0 < t \leq DT$ shown in Figure B.7, the switch S is ON and the diode is OFF: an equivalent ideal circuit is shown in Figure B. 8. When the switch is ON, the voltage across the diode V_D is approximately equal to $-V_O$ and therefore the diode is reverse biased.

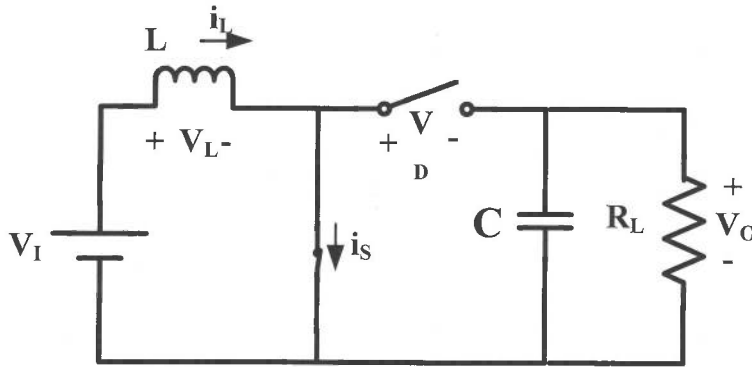


Figure B. 8. Equivalent circuit when the switch is ON and the diode is OFF for boost converter

The voltage across the switch is V_S and the diode current is zero. The voltage across the inductor, L , is:

$$v_L = V_I = L \frac{di_L}{dt} \quad (B2.1)$$

Thus the current through the inductor increases linearly with gradient V_I/L , and the magnetic energy also increases. The same current flows through both switch and inductor:

$$i_S = i_L = \frac{1}{L} \int_0^t v_L dt + i_L(0) = \frac{1}{L} \int_0^t V_I dt + i_L(0) = \frac{V_I}{L} t + i_L(0) \quad (B2.2)$$

$$i_L = (DT) = \frac{V_I DT}{L} + i_L(0) \quad (B2.3)$$

Where $i_L(0)$ is the initial inductor current at $t = 0$. The maximum current through the inductor is given in Equation (B2.3). The peak-to-peak value of the ripple on the inductor current is expressed as:

$$\Delta i_L = i_L(DT) - i_L(0) = \frac{V_I DT}{L} = \frac{V_I D}{f_s L} = \frac{V_O D}{M_{VDC} f_s L} = \frac{V_O D(1-D)}{f_s L} \quad (\text{B2.4})$$

For fixed values of V_O , f_s and L , by differentiation:

$$\frac{d\Delta i_L}{dD} = \frac{V_O}{f_s L} (1-2D) \quad (\text{B2.5})$$

To obtain the maximum value of Δi_L with change in D , we set this derivative to zero and find that the corresponding value of D to be 0.5. The maximum value of Δi_L is given in Equation (B2.6). As the value of D is increased from 0 to 1, the peak-to-peak value of the ripple current in the inductor increases from zero, reaches a maximum at $D = 0.5$, and then decreases back to zero.

$$\Delta i_{L\max} = \frac{V_O}{4f_s L} \quad (\text{B2.6})$$

The diode voltage is given in Equation (B2.7).

$$v_D = -V_O \quad (\text{B2.7})$$

The maximum value of the switch current can be found from the fact that the average value of the inductor current I_L is equal to the dc input current I_I .

$$I_{SM} = I_I + \frac{\Delta i_L}{2} = \frac{I_O}{1-D} + \frac{\Delta i_L}{2} \quad (\text{B2.8})$$

For continuous mode, the inductor current i_L is terminated at $t = DT$, when the driver turns the switch off. Since $i_L(DT)$ is not zero when the switch is turned off, it acts in a

similar manner to a current source and turns the diode on. The increase in the magnetic energy of the inductor is:

$$\Delta W_{L(m)} = \frac{1}{2} L [i_L^2(DT) - i_L^2(0)] \quad (B2.9)$$

B.2.3 Time interval $DT < t \leq T$

At $t = DT$, the gate-to-source voltage turns the switch OFF. Again the inductor acts as a current source and turns the diode ON. Figure B. 9 shows an equivalent ideal circuit of a lossless converter for this time interval.

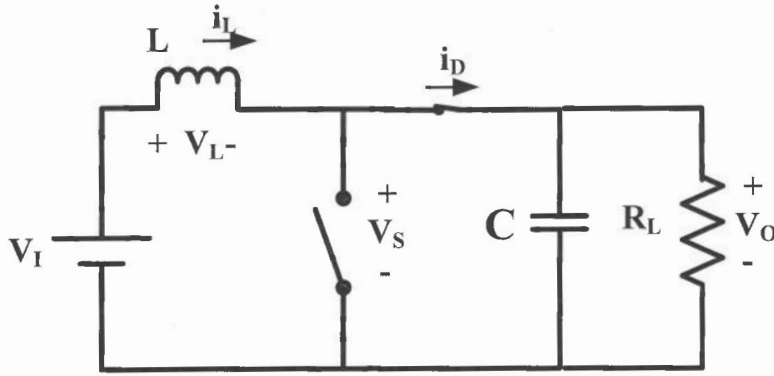


Figure B. 9. Equivalent circuit when the switch is OFF and the diode is ON for boost converter
The diode voltage v_D and switch current i_S are zero. The inductor current decreases with a gradient of $(V_I - V_O)/L$. During this time interval, energy is transferred to the load resistance and capacitor from the inductor L . The magnetic energy stored in the inductor discharges during this time. The voltage across the inductor L is:

$$v_L = V_I - V_O = L \frac{di_L}{dt} < 0 \quad (B2.10)$$

v_L is less than zero because in a boost converter, V_O is always greater than V_I . The diode and inductor currents are equal:

$$i_D = i_L = \frac{1}{L} \int_{DT}^t v_L dt + i_L(DT) = \frac{1}{L} \int_{DT}^t (V_I - V_O) dt + i_L(DT) = \frac{V_I - V_O}{L} (t - DT) + i_L(DT) \quad (B2.11)$$

Where $i_L(DT)$ is the initial inductor current at $t = DT$.

The peak-to-peak value of the inductor ripple current is:

$$\Delta i_L = i_L(DT) - i_L(T) = \frac{(V_O - V_I)(1-D)T}{L} = \frac{V_O D(1-D)}{f_s L} \quad (B2.12)$$

Where $V_I = V_O (1 - D)$.

The voltage across the switch S is as given in Equation (B2.13). The maximum switch and diode currents are equal and given in Equation (B2.14).

$$v_S = V_O = V_{SM} \quad (B2.13)$$

$$I_{DM} = I_{SM} = I_I + \frac{\Delta i_L}{2} = \frac{I_O}{1-D} + \frac{\Delta i_L}{2} \quad (B2.14)$$

For the worst case, the equation (B2.14) becomes:

$$I_{DM\max} = I_{SM\max} = I_{I\max} + \frac{\Delta i_{L\max}}{2} = \frac{I_{O\max}}{1-D\max} + \frac{\Delta i_{L\max}}{2} \quad (B2.15)$$

At $t = T$ the driver turns the switch on. The decrease in magnetic energy stored in the inductor over the time interval $DT < t \leq T$ is as given in Equation (B2.16). For steady state conditions, it would be expected that the increase in magnetic energy stored in the inductor when the switch S is ON and the diode is OFF ($0 < t \leq DT$) is equal to the decrease in the magnetic energy when the switch is OFF and the diode is ON ($DT < t \leq T$).

$$\Delta W_{L(out)} = \frac{1}{2} L [i_L^2(DT) - i_L^2(T)] \quad (B2.16)$$

B.2.4 DC voltage transfer function of the boost converter for CCM

The average voltage across the inductor in the steady state is:

$$V_{L(AV)} = \frac{1}{T} \int_0^T v_L dt = 0 \quad (\text{B2.17})$$

Referring back to relative areas in Figure B.7:

$$V_I DT = (V_O - V_I)(1 - D)T \quad (\text{B2.18})$$

Which simplifies to:

$$V_O = \frac{V_I}{1 - D} \quad (\text{B2.19})$$

For a lossless converter, $V_I I_I = V_O I_O$. Hence, from Equation (B2.19), the dc voltage transfer function (or the voltage conversion ratio) of the lossless boost converter is given by:

$$M_{VDC} \equiv \frac{V_O}{V_I} = \frac{I_I}{I_O} = \frac{1}{1 - D} \quad (\text{B2.20})$$

Since $0 \leq D \leq 1$, we have $1 \leq M_{VDC} \leq \infty$.

3 Appendix C

C.1. Rule base for fuzzy logic controller

1. If (power_demand_A is A5) and (Battery_V is V27) then (Output_power_of_bidirectional_converter_A is A-5) (1)
2. If (power_demand_A is A5) and (Battery_V is V30) then (Output_power_of_bidirectional_converter_A is A-5) (1)
3. If (power_demand_A is A5) and (Battery_V is V32) then (Output_power_of_bidirectional_converter_A is A-5) (1)
4. If (power_demand_A is A5) and (Battery_V is V35) then (Output_power_of_bidirectional_converter_A is A1.5) (1)
5. If (power_demand_A is A5) and (Battery_V is V37) then (Output_power_of_bidirectional_converter_A is A1.5) (1)
6. If (power_demand_A is A5) and (Battery_V is V38) then (Output_power_of_bidirectional_converter_A is A1.5) (1)
7. If (power_demand_A is A10) and (Battery_V is V27) then (Output_power_of_bidirectional_converter_A is A-5) (1)
8. If (power_demand_A is A10) and (Battery_V is V30) then (Output_power_of_bidirectional_converter_A is A-5) (1)
9. If (power_demand_A is A10) and (Battery_V is V32) then (Output_power_of_bidirectional_converter_A is A-5) (1)
10. If (power_demand_A is A10) and (Battery_V is V35) then (Output_power_of_bidirectional_converter_A is A3) (1)
11. If (power_demand_A is A10) and (Battery_V is V37) then (Output_power_of_bidirectional_converter_A is A3) (1)
12. If (power_demand_A is A10) and (Battery_V is V38) then (Output_power_of_bidirectional_converter_A is A3) (1)
13. If (power_demand_A is A15) and (Battery_V is V27) then (Output_power_of_bidirectional_converter_A is A-5) (1)
14. If (power_demand_A is A15) and (Battery_V is V30) then (Output_power_of_bidirectional_converter_A is A-5) (1)
15. If (power_demand_A is A15) and (Battery_V is V32) then (Output_power_of_bidirectional_converter_A is A-5) (1)

16. If (power_demand_A is A15) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A4.4) (1)
17. If (power_demand_A is A15) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A4.4) (1)
18. If (power_demand_A is A15) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A4.4) (1)
19. If (power_demand_A is A20) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
20. If (power_demand_A is A20) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
21. If (power_demand_A is A20) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
22. If (power_demand_A is A20) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A6.2) (1)
23. If (power_demand_A is A20) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A6.2) (1)
24. If (power_demand_A is A20) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A6.2) (1)
25. If (power_demand_A is A25) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
26. If (power_demand_A is A25) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
27. If (power_demand_A is A25) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
28. If (power_demand_A is A25) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
29. If (power_demand_A is A25) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A9.2) (1)
30. If (power_demand_A is A25) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A10.9) (1)
31. If (power_demand_A is A30) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
32. If (power_demand_A is A30) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A-5) (1)

33. If (power_demand_A is A30) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
34. If (power_demand_A is A30) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A9.2) (1)
35. If (power_demand_A is A30) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A10.9) (1)
36. If (power_demand_A is A30) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A10.9) (1)
37. If (power_demand_A is A35) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
38. If (power_demand_A is A35) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
39. If (power_demand_A is A35) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A10.9) (1)
40. If (power_demand_A is A35) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A10.9) (1)
41. If (power_demand_A is A35) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A13.6) (1)
42. If (power_demand_A is A35) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A13.6) (1)
43. If (power_demand_A is A40) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
44. If (power_demand_A is A40) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A-5) (1)
45. If (power_demand_A is A40) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A13.6) (1)
46. If (power_demand_A is A40) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A12.2) (1)
47. If (power_demand_A is A40) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A13.6) (1)
48. If (power_demand_A is A40) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A13.6) (1)
49. If (power_demand_A is A45) and (Battery_V is V27) then
(Output_power_of_bidirectional_converter_A is A-5) (1)

50. If (power_demand_A is A45) and (Battery_V is V30) then
(Output_power_of_bidirectional_converter_A is A4.4) (1)

51. If (power_demand_A is A45) and (Battery_V is V32) then
(Output_power_of_bidirectional_converter_A is A14.7) (1)

52. If (power_demand_A is A45) and (Battery_V is V35) then
(Output_power_of_bidirectional_converter_A is A14.8) (1)

53. If (power_demand_A is A45) and (Battery_V is V37) then
(Output_power_of_bidirectional_converter_A is A15) (1)

54. If (power_demand_A is A45) and (Battery_V is V38) then
(Output_power_of_bidirectional_converter_A is A15) (1)

C.2. Table of rule base for fuzzy logic controller

Current demand (A)	Battery voltage (V)	Output current of bidirectional converter (A)
1. If 5	and 27	then -5
2. If 5	and 30	then -5
3. If 5	and 32	then -5
4. If 5	and 35	then 1.5
5. If 5	and 37	then 1.5
6. If 5	and 38	then 1.5
7. If 10	and 27	then -5
8. If 10	and 30	then -5
9. If 10	and 32	then -5
10. If 10	and 35	then 3
11. If 10	and 37	then 3
12. If 10	and 38	then 3
13. If 15	and 27	then -5
14. If 15	and 30	then -5
15. If 15	and 32	then -5
16. If 15	and 35	then 4.4
17. If 15	and 37	then 4.4
18. If 15	and 38	then 4.4
19. If 20	and 27	then -5
20. If 20	and 30	then -5
21. If 20	and 32	then -5
22. If 20	and 35	then 6.2
23. If 20	and 37	then 6.2
24. If 20	and 38	then 6.2
25. If 25	and 27	then -5

26. If 25	and 30)	then -5
27. If 25	and 32	then -5
28. If 25	and 35	then -5
29. If 25	and 37	then 9.2
30. If 25	and 38	then 10.9
31. If 30	and 27	then -5
32. If 30	and 30	then -5
33. If 30	and 32	then -5
34. If 30	and 35	then 9.2
35. If 30	and 37	then 10.9
36. If 30	and 38	then 10.9
37. If 35	and 27	then -5
38. If 35	and 30	then -5
39. If 35	and 32	then 10.9
40. If 35	and 35	then 10.9
41. If 35	and 37	then 13.6
42. If 35	and 38	then 13.6
43. If 40	and 27	then -5
44. If 40	and 30	then -5
45. If 40	and 32	then 13.6
46. If 40	and 35	then 12.2
47. If 40	and 37	then 13.6
48. If 40	and 38	then 13.6
49. If 45	and 27	then -5
50. If 45	and 30	then 4.4

51. If 45	and 32	then 14.7
52. If 45	and 35	then 14.8
53. If 45	and 37	then 15
54. If 45	and 38	then 15