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Department of Mechatronic Engineering

Designing a Hydrogen Fuel Cell Control System

Final year project (FYP 13-11)

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Declaration

We hereby declare that the work contained in this report is original; researched and documented by the undersigned students. It has not been used or presented elsewhere in any form for award of any academic qualification or otherwise. Any material obtained from other parties have been duly acknowledged. We have ensured that no violation of copyright or intellectual property rights have been committed.

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Abstract

Operation of a hydrogen fuel cell requires the control of factors that affect the safety performance, efficiency and lifespan of the proton exchange membrane. This proposal looks into different control strategies that will be employed for variable power delivery from the hydrogen fuel cell with consideration of safety, efficiency and longevity of operation. The project will go into modelling of the control system and simulation of different operating conditions to determine the best controllers along with the control parameters. The project also looks into control strategies such as neural networks, linear quadratic regulator and PID control to optimize on factors such as performance and efficiency. Each of the control strategies will be modeled and tested to select the best performing controller which will be developed for the hydrogen fuel cell stack.

1 Introduction

1.1 Background

Research on Fuel cells started in 1801 when British Chemist Humphry Davy was setting up experiments to assist him in separating several materials using voltaic piles. The experiments set the background for the development of fuel cells which Christian Friedrich Schönbein worked on in 1838. Sir William Grove was the first scientist to prove that reaction between hydrogen and oxygen produced electricity in 1939. He carried out experiments on water electrolysers and fuel cells using his background on electrolysis to come up with a reverse process to generate electricity. He succeeded in building a device that combined water and hydrogen to generate electricity. The new device was originally called a gas battery, but later was renamed the fuel cell.

The first operational fuel cell was developed by Charles Langer and Ludwig Mond. The duo developed a functional fuel cell, obtaining fuel capacity of 0.73V at 20A/m2. Francis Bacon advanced the Mond and Langer fuel cell in 1958, which was later used in the Apollo mission in 1969. Since then, the space agencies have been using fuel cells to power the space crafts and provide water for the astronauts.

With the current global challenge in the energy sector, there is an increasing need for power generation with minimal pollution and environmental degradation. As a way of mitigating environmental pollution and providing energy shortage routes, Fuel Cell technologies have been considered as elements of alternative energy systems. These technologies capitalize on high efficiencies and low emissions.

Fuel cells are increasingly becoming a promising alternative to internal combustion engines (ICEs) and thus are considered for transportation (automotive, marine and aerospace) applications. They are also being considered for distributed power generation for residential homes and industries. Another promising use of FC stacks is for electricity storage in conjunction with electrolyzers and hydrogen accumulators.

Power generation from Fuel Cells (FC) necessitates the integration of chemical, fluid, mechanical, thermal, electrical, and electronic subsystems. This integration presents many challenges and opportunities in the mechatronics engineering field. A fuel cell system is made up of a water and heat management system, an air system, a humidifier system and a hydrogen in-out let system. For optimum operation of the Fuel cell, some factors must be controlled - these are: the hydrogen flow, air supply, water cooling temperature, membrane temperature and humidity. Control strategies are therefore imminent so that the FC operates within some established limits such as electric power, pressure of the fuel gas and amount of air for the anode chemical reaction.

There are several types of fuel cells, each using a different chemistry. The common types of fuel cells are:

- Polymer electrolyte fuel cells
- Direct methanol fuel cells
- Alkaline fuel cells
- Phosphoric acid fuel cells
- Solid oxide fuel cells
- Reversible fuel cells
- Molten carbonate fuel cells

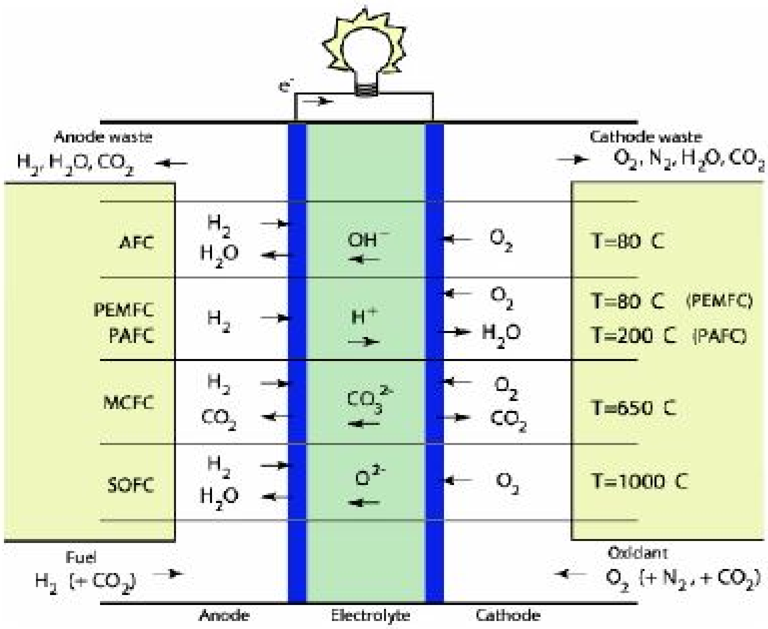

Figure 1.1: fuel cell types and their respective operating temperatures [1]

Polymer electrolyte fuel cells and alkaline fuel cells were the commonly used fuel cells for space missions. Development of fuel cells for commercial activities started in 2007, with an interest to develop fuel cells for automobile applications. The Polymer Electrolyte membrane (PEM) fuel cell is commonly used to power vehicles. Currently, the Polymer Electrolyte Membrane (PEM) Fuel Cells (also known as Proton Exchange Membrane Fuel Cells) are considered by many to be in a relatively more developed stage for ground vehicle applications. PEM Fuel Cells have high power density, solid electrolyte, long cell and stack life, as well as low corrosion. They have greater efficiency when compared to heat engines and their use in modular electricity generation and propulsion of electric vehicles is promising. This proposal will focus on the design and development of a control system for a Proton Exchange Membrane Fuel Cell (PEMFC).

1.2 Basic Operation Principle of a Hydrogen Fuel Cell

Fuel cells convert chemical energy sources directly to electricity. A fuel cell consists of an electrolyte sandwiched between two electrodes. The electrolyte has a special property which allows protons to pass through while blocking electrons. Hydrogen gas passes over one electrode, i.e. an anode, and with the help of a catalyst, separates into electrons and hydrogen protons.

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{1.1}$$

The protons flow to the other cathode through the electrolyte while the electrons flow through an external circuit, thus creating electricity. The hydrogen protons and electrons combine with oxygen flow through the cathode, and produce water.

$$O_2 + 4H_2 + 4e^- \rightarrow 2H_2O \tag{1.2}$$

The overall reaction of the fuel cell is given by:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1.3}$$

1.3 Problem statement

As a measure to curb pollution due to the industrialization and transportation sectors, world governments are turning to alternative sources of energy. These alternative sources of energy should drastically reduce the pollution rates by cutting down emissions. Fuel cell technology is one such example of alternative sources of energy. A fuel cell uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity. Moreover, fuel cells can operate at higher efficiencies than combustion engines and can convert the chemical energy in the fuel directly to electrical energy with efficiencies capable of exceeding 60%. Fuel cells have lower or zero emissions compared to combustion engines.

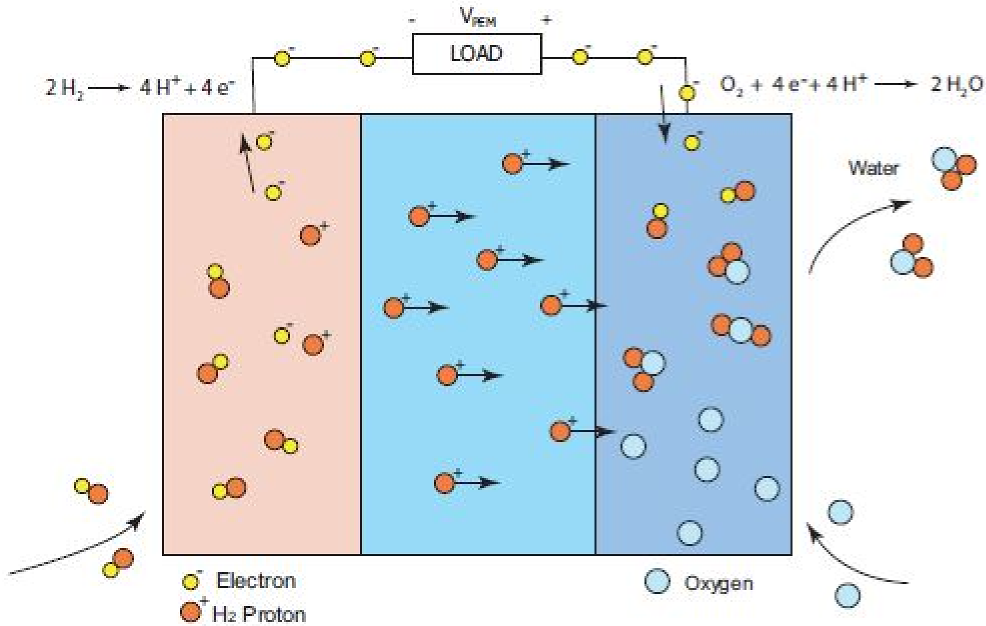

Figure 1.2: Fuel Cell Reactions [2]

The various departments of energy, however, have to work closely with national laboratories, universities, and industry partners to overcome critical technical barriers to fuel cell development. These barriers are cost, performance, and durability which are still key challenges in the fuel cell industry.

This design proposal seeks to provide a solution to improving the fuel cell's performance by improving the robustness and efficiency of the Fuel Cell stack system for real world conditions through precise control of reactant flow and pressure, stack temperature, and membrane humidity.

1.4 Objectives

1.4.1 Main Objectives

1. To develop a Hydrogen Fuel cell control system.

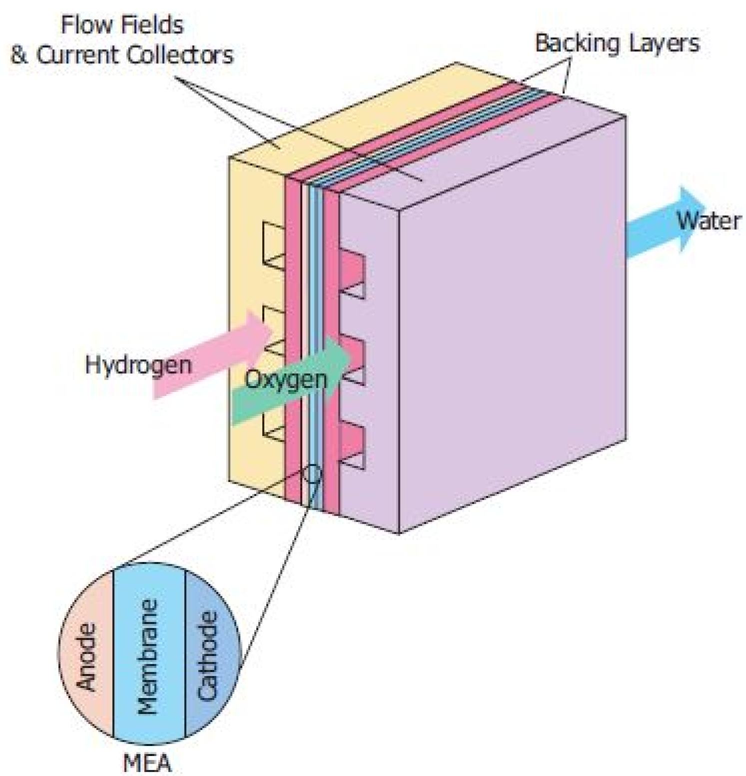

Figure 1.3: Fuel Cell Structure [2]

1.4.2 Specific Objectives

1. To design and additively manufacture a PEMFC prototype which can be adapted for domestic use and scaled for industrial applications.

2. To design and fabricate supporting control electronics for the Hydrogen Fuel Cell.

3. To achieve precise control of reactant flow and pressure, stack temperature, and membrane humidity.

4. To simulate and test alternative control strategies for the Hydrogen fuel cell.

1.5 Justification of the study

Additive manufacturing offers the ability to produce intricate products and parts with lower development costs, shorter lead times, less energy consumed during manufacturing as well as less material waste. This method can be used to manufacture delicate components such as the bipolar plates with elimination of the risks involved such as breakage of brittle Graphene material during production.

Precise control of reactant flow and pressure, stack temperature, and membrane humidity will increase the fuel cell's robustness as well as efficiency.

The goal of this research is to develop physic-based dynamic models of fuel cell systems and fuel processor systems and then apply multivariable control techniques to study their behavior. The analysis will give insight into the control design limitations and provide guidelines for the necessary controller structure and system re-design.

2 Literature Review

In a (Proton Electron Membrane)PEM fuel cell stack, chemical energy from the reaction between hydrogen and oxygen is converted directly into electric energy. Water and heat are produced as by-products.

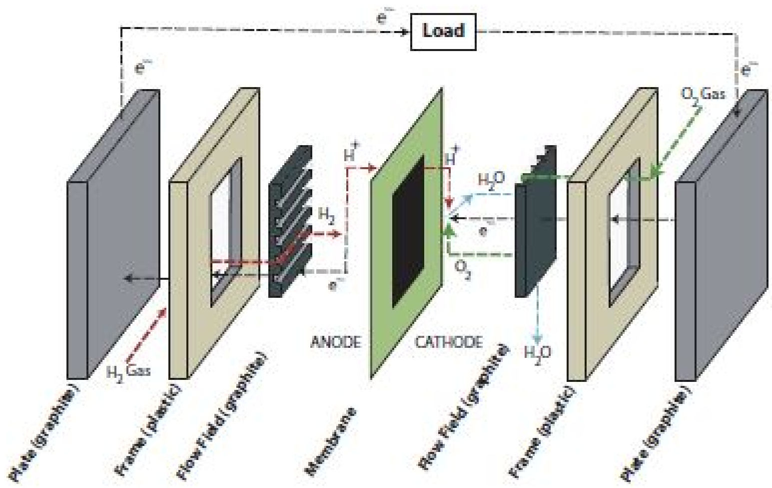

Figure 5: Fuel cell component description

Figure 2.1: Fuel cell component description [1]

3 Methodology

3.1 System Modelling

The fuel cell system model will be obtained from governing equations from which a transfer function will be generated from the linearized model. The transfer function will be used to generate a state space model for the system.

The system will then be represented in matlab and the controllers designed will be tested on the system to observe the effectiveness of each control method.

There are two types of models which have been proposed to investigate fuel cell technology via simulation. The approaches are detailed lumped parameter dynamic models;and black-box models based on system identification. The latter commonly expresses as NARX (Nonlinear Auto Regressive with eXogenous input) or ARMAX (Auto Regressive Moving Average with eXogenous input) equations. This work addresses both modelling approaches by presenting an ARMAX model for the black-box modelling approach and a detailed mechanistic model for the dynamic modelling approach.

3.1.1 ARMAX Model

From a system viewpoint, hydrogen is an input variable and is fed at an adjustable flow rate NH . Oxygen is also an input and can be represented by NA where a fuel cell uses the oxygen content of air. Voltage and current are then considered the system outputs. Franklin et al [4], represent this as Multiple Input Multiple Output (MIMO) System as shown in the Figure 3.4 below.

The relationship between the inputs (N_A and N_H) and the outputs (I_c and V_c), while R represents the internal resistance. The system can be represented using the following

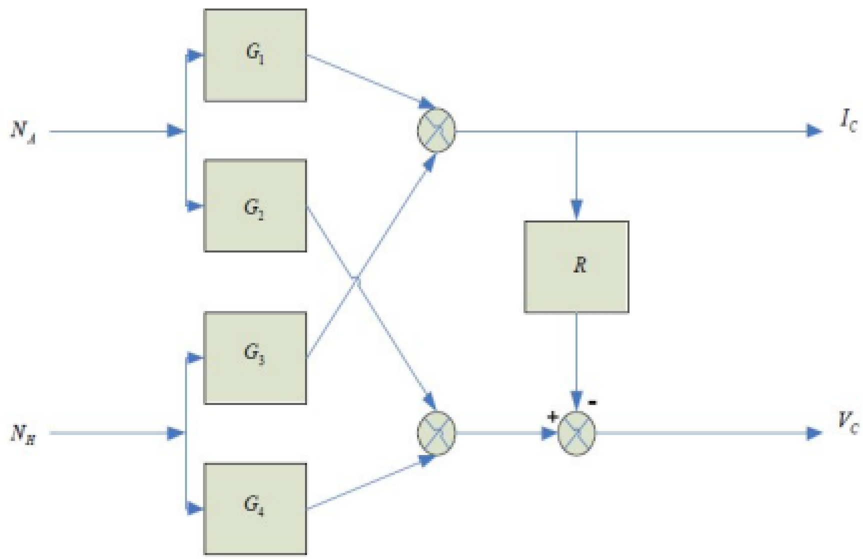

Figure 3.1: MIMO representation of fuel cell [3]

equations:

$$V_c = G_2 N_A + G_4 N_H + R I_C \tag{3.1}$$

$$I_C = G_1 N_A + G_3 N_H \tag{3.2}$$

Equation 3.1 and 3.2 will be used as a basis for system identification and controller design.

3.2 Simulations

From the generated models on matlab, simulations will be performed using the different controllers and the responses and other metrics will be plotted out for further analysis. Metrics such as rise time, settling time and stochastic response will be observed to determine the system performance.

3.3 Sensors

Sensors will be used to collect data from the system as it runs. These include:

- Humidity sensor
- Temperature sensor
- Flow rate sensor
- Pressure sensors
- Voltage sensor
- Current sensor

These sensors will be used by the controller to observe system performance and optimize for each parameter as well as the performance requirements.

3.4 Data Analysis

The data collected from the simulations and sensors will be analysed using custom software created using jupyter notebooks. Graphs will be generated to compare the performance of each controller and evaluation of the selected controller.

4 Expected Outcomes

1. The controller for the hydrogen fuel cell will be developed and tested
2. The controller supporting circuitry will be developed with a custom printed circuit board.
3. Hydrogen fuel cell system performance will be optimized using the controller.

5 Proposed Budget

Item	Quantity	Price
Assembled PCB microcontroller (PIC)	1	10,000
Tough PLA filament for case	2	12,600
Micro precision current sensor	1	200
Pressure transducer	2	6,000
Total		28,800

Table 5.1: Proposed budget

6 Work Plan

Year	2021						2022					
Month	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEPT**	**NOV**	**DEC**
Literature Review												
Proposal Refinement												
System Modelling												
Controller modelling												
Simulation												
Fabrication and Testing												
Data Collection and Analysis												
Final year report preparation and submission												
Presentation												

Table 6.1: Workplan table

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