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College of Engineering and Technology

School of Mechanical, Materials, and Manufacturing Engineering

Department of Marine Engineering and Maritime Operations

Advanced Condition Based Predictive Maintenance of Electric Motors in Autonomous Ships

Project Proposal (MR-PRO-21-011)

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Declaration

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Abstract

Maritime shipping is employed to move food, medicines, and far more at the heart of world trade. For growth and development, economical mechanisms of shipping are followed, particularly within the developing world. Machinery and equipment breakdown that occur during marine transportation cause delays, swings in supplies, production, and trigger infinite downstream effects on entire supply chains. In the shipping industry planned and reactive maintenance that is primarily practiced requires halting of vessel operations for a number of days despite the fact that no fatigue or machinery and equipment breakdown is observed. Having seen the importance of motors that are widely utilized in ships auxiliary machinery, the project focuses on creating failure predictions, additionally determining remaining useful life (RUL) for motors aboard ships, albeit also quite fascinating is the role this research plays in the monitoring of equipment on autonomous ships. This is made possible with developments in information and technology. Massive amounts of data is collected and can facilitate condition based monitoring (CBM), conduct analysis on best performance and comprehensively diagnose ship engine room equipment.

Keywords: efficiency, condition monitoring, remaining useful life, autonomous ships, performance.

1 Introduction

1.1 Background

As the world's industries push the boundaries of optimization and efficiency, the exponential increase in computational ability and technology The automation of "higher-level" tasks that require human intellect is now possible. This headway brings unmanned autonomous vessels within the Maritime Industry closer to mass production. The practicality of autonomous vessels can only be achieved with constant awareness of the performance and operating state of machinery in the engine room (CBM). Observations of industry practices display that industry experience in reliability is heavily based on trial-and-error test procedures.

Most of the reliability research in industry still focuses on two distinct periods of the product life. The warranty period, where most of the failures are due to product malfunctions or quality related problems, and, wear-out period, where the failures are due excessive wear and use(1). Using sensors and logging software the condition of equipment is assessed as frequently as needed, enabling efficient analysis of data that facilitates planning of predictive maintenance on-board vessels.

The electric motor is the most used device for conversion from electric to mechanical energy and is used for electric propulsion, powering thrusters for station keeping, and different on-board equipment on hundreds of ships. Typically, 80-90 percent of the load installations will be electric motors.[2]

Smart organizations know they can no longer afford to see maintenance as just an expense. Rather, maintenance must be integrated within the business cycle in order to guarantee predictability, growth and increase the overall quality of operations. Moving from a regime of scheduled rule-based maintenance via on-condition maintenance and

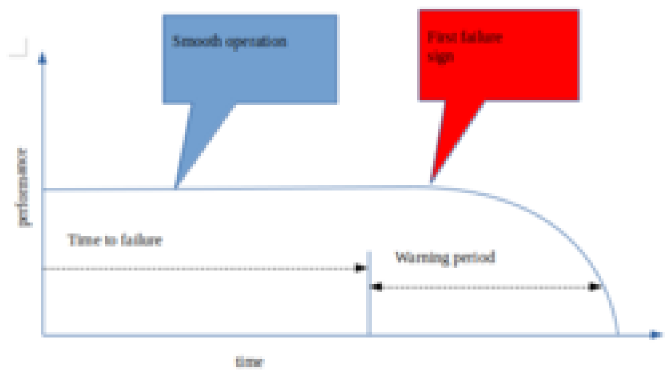

Figure 1.1: Fuel Cell Structure [?]

ultimately to a data-driven risk-based regime can lead to more accurate and timely maintenance tasks. This smarter view of maintenance allows for achieving many practical advantages leading to lower costs and increased safety and availability of ship systems.[3]

Making failure predictions and determination of remaining useful life (RUL), realizes significant benefits not limited to: work=style reforms, reduction in crew workload in that monitoring is done autonomously, improved safety from preventing accidents before they happen, and ensuring efficient optimal operation. [?] In future more equipment will be added in a modular manner to realize better optimal performance.

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

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

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

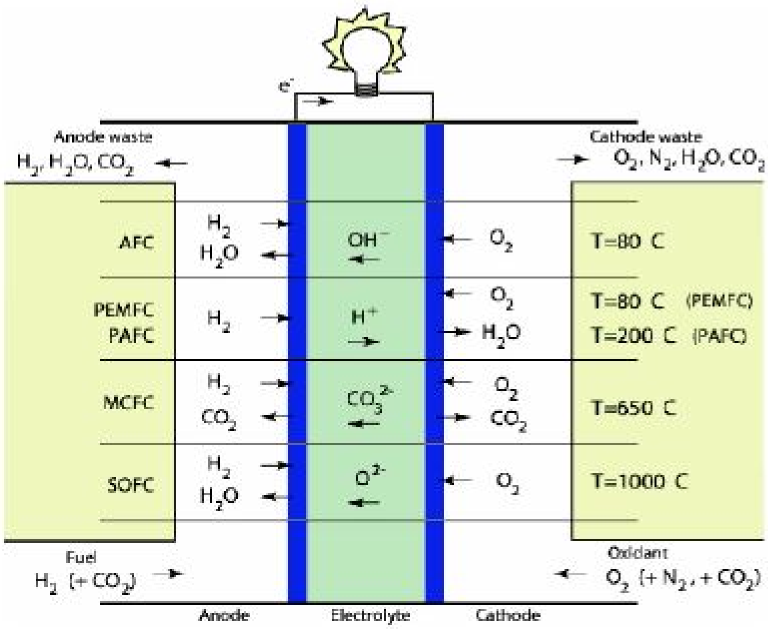

Figure 1.2: Fuel cell types and their respective operating temperatures [?]

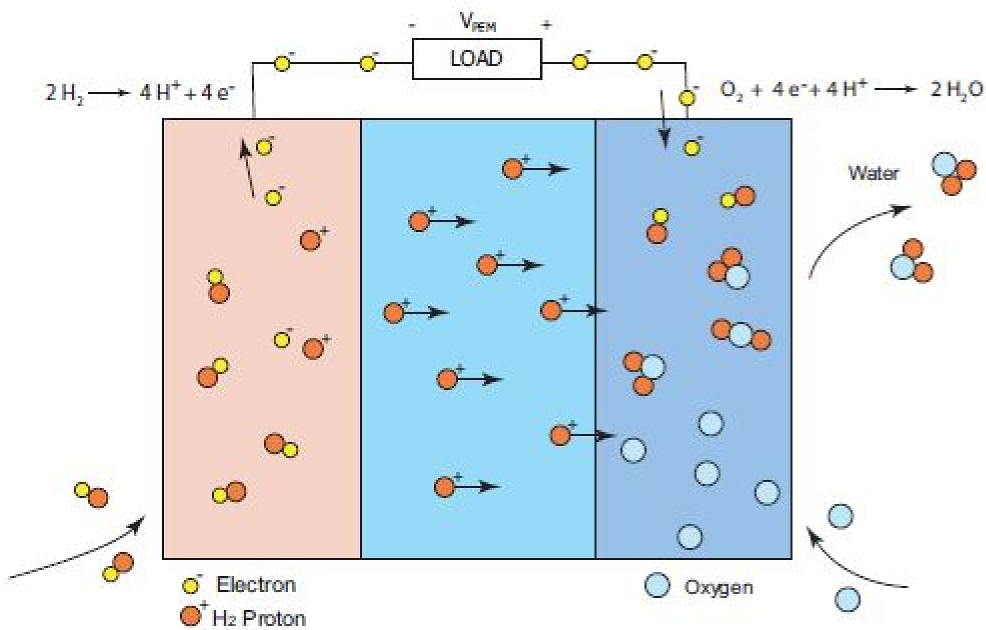

Figure 1.3: Fuel Cell Reactions [?]

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

Out of 880 accidental errors in ship related incidents 62Engine room failures are caused by a majority of three ways, either by: Natural mechanical failure, Electrical failure of components and whole systems, Human negligence, and poor competency in engine room procedures, Inaccurate diagnosis, and sub-par prevention measures.

These accidents are more notably recognized when they result in internationally felt effects such as oil spills damaging large swathes of marine ecosystems or when loss of life of crew members is realised. But with greater significance but less spoken of - the loss of millions in profits in maintenance and shipping costs incurred to the vessel's owner that would otherwise have been used more productively.

While it is impractical to try and eliminate accidents in the engine room,this design proposal seeks to provide a solution to improving efficiency and mitigating downtime by implementing strategies to reduce human through the automation of engine room condition monitoring[**?**].

1.4 Objectives

1.4.1 Main Objectives

1. To develop monitor the health of ship motors improving reliability and preventing downtime in ships.

1.4.2 Specific Objectives

1. To develop a predictive maintenance algorithm for electric motors in ships.
2. To model a modular framework onto which various equipment will be added to achieve predictive maintenance in the entire ship's engine room.
3. To design a product that has seamless integration on multiple motors

1.5 Justification of the study

Electric motors serve as a critical component for any facility. However, electric motors can be prone to any number of issues that lead to motor faults and failures. Failures disrupt business operations, decrease productivity, and adversely impact a company's bottom line.

Motor inspection processes have shifted from manual scrutiny to semi automated and fully-automated inspection. This will replace the time consuming task of manual review, significantly increasing productivity while preventing missed inspection as well as errors. Traditionally maintenance involves routine inspection and repair done manually. This cannot completely prevent the risk of machine downtime and will also result in the unnecessary early replacement of usable parts. [4]

The purpose of this project is to alert about problems occurring in the motor and trying to mitigate the risk of unexpected failure. A well planned predictive maintenance is the key to long life operation of motors. In ships unexpected failure causes downtime which deeply eats into profits.The traditional approach is to repair and replace equipment after a period of time but this cannot prevent downtime due to malfunctions, which put a halt to operations and incur massive losses. Advanced monitoring is implemented on parts that are about to break down and can be discovered in advance to accurately determine the time for repair and risk of unexpected shutdown can be prevented. [1]

Although Reactive and preventive maintenance will always have a part in operations,Predictive maintenance is the next big step forward in the evolution of asset management. In fact, the ability to connect assets and feed information into a central system gives organizations the power to turn data into powerful insights and automatically take corrective, preventive or predictive action.

2 Literature Review

2.1 Operation, Subsystems and Parameters

Condition monitoring is a type of maintenance inspection where an operational asset is monitored and the data obtained is analyzed to detect signs of degradation, diagnose the cause of faults, and predict for how long it can be safely or economically run. There are five general categories of Condition Monitoring techniques—vibration monitoring and analysis; visual inspection and nondestructive testing; performance monitoring and analysis; analysis of wear particles in lubricants and of contaminants in process fluids; and electrical plant testing. Condition Monitoring needs good quality data such as that obtained by carefully run tests. However, much useful information can often be obtained from a plant's permanent instrumentation once repeatability is established. [?].

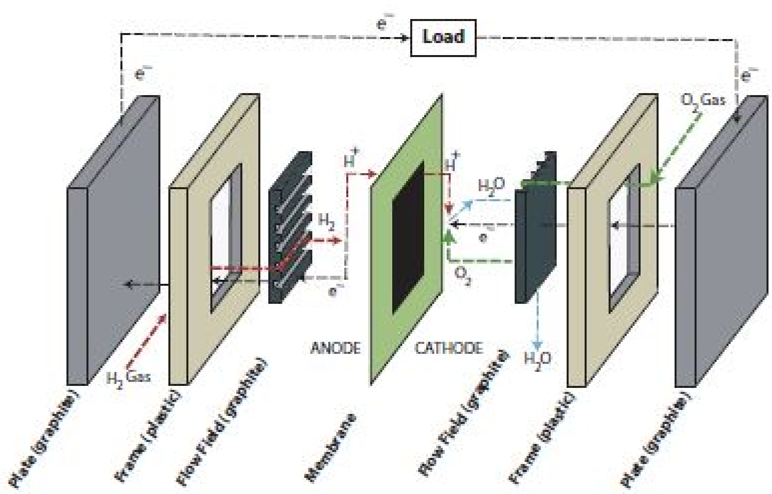

Figure 2.1: Fuel cell component description [?]

Remaining Useful Life (RUL) is the time remaining for a component to perform its functional capabilities before failure. The concept of Remaining Useful Life (RUL) is used to predict life-span of components (of a service system) with the purpose of minimising catastrophic failure events in both manufacturing and service sectors. Our proposal involves acquiring real data from a normal working pump at its different stages in life. This will be done using multiple sensors attached to the pump at different times under different working conditions. The data include temperature, vibration and pressure. Over time, the installed sensors will generate more and more data which can be used to improve the initial models and make near-perfect failure predictions. [**?**].

Currently the industry is majorly relying on sensors for condition monitoring which has facilitated decision making under time constraints. The time between the point where a potential failure occurs and the point where it deteriorates into a functional failure can be seen as an opportunity window during which decision making algorithms can recommend actions with the aim to eliminate the anticipated functional failure or mitigate its effect. The system can record and monitor vibration and temperature conditions of an industrial motor and transmit the data through a wireless network to a data logging center. The current prototype was developed using open source software and hardware and can successfully identify abnormal motor conditions from sensor input values that exceed predefined setpoints.

$$O_2 + H^+ + 4e^- \rightarrow 2H_2O \tag{2.1}$$

The migration of electrons produces electricity. The overall reaction of the fuel cell is:

$$2H_2 + O_2 \rightarrow 2H_2O + Heat. \tag{2.2}$$

The electrical characteristics of fuel cells are given in the form of a polarization curve, shown in Figure 2.2 , which is a plot of cell voltage versus cell current density (current per unit cell active area) at different reactant pressures and flows.

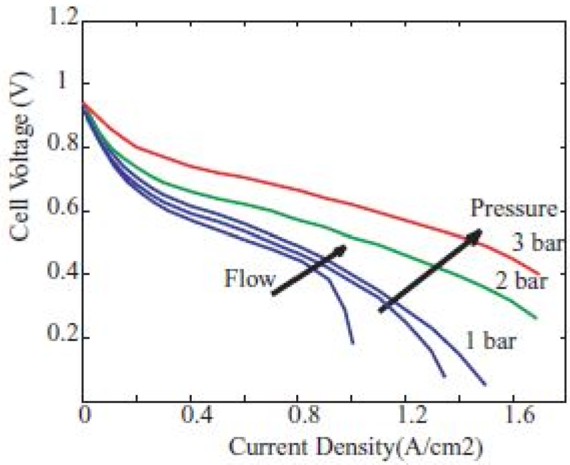

Figure 2.2: Fuel cell component description [?]

Stack temperature and membrane water content affect the fuel cell voltage [?]. The difference between the actual voltage and the ideal voltage represents the loss in the cell which turns into heat. (The ideal standard voltage for a fuel cell in which H2 and O2 react is 1.18 V when the resulting water product is in gaseous form.)

As more current is drawn from the fuel cell, the voltage decreases, due to fuel cell electrical resistance, low reaction rate and, inefficient reactant gas transport,. Lower voltage indicates lower efficiency of the fuel cell, therefore low load (low current) operation is preferred. Operation at low load requires a large fuel cell stack and has detrimental consequences to the overall volume, weight, and cost.

To avoid over-sizing the FC stack, a series of actuators such as valves, pumps, blowers, expander vanes, fan motors, humidifiers and condensers are used to control critical FC parameters for a wide range of current, and thus, power setpoints. The auxiliary actuators are needed to make fine and fast adjustments to satisfy reliability standards, performance and safety that are independent of age and operating conditions of the FC. The resulting multivariate design and control synthesis task, also known as balance of plant (BOP), is complex because of subsystem interactions, conflicting objectives, and lack of sensors.

Main Control among the main FC subsystems are:

- reactant supply system
- heating and cooling system
- humidification system
- Power management System

The main control variables in FC systems are:

- Stack temperature
- Membrane humidity
- Accumulation of water and nitrogen in the anode side.

These variables are the most important factors for any efficiency and lifetime of FC stacks.

Previous research has concluded that since the fuel cell is a passive power source, a simple feed forward control strategy is used to control the air supply and A PI-feedback algorithm is developed to control the cooling water temperature. The research further concludes that the control strategies need to be further optimized basing on a nonlinear dynamic model.

Dr. J.T. Pukrushpan et al.[?] studied modelling and control for PEM fuel cell stack systems, and published several papers. They proposed a nonlinear dynamic model to describe the PEM fuel cell system, and designed feedback controllers based on the model.

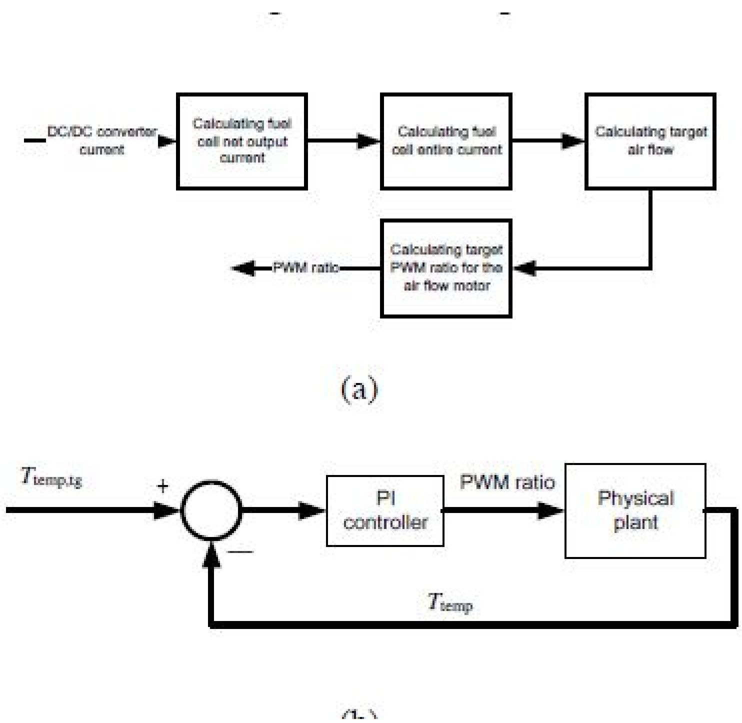

Figure 2.3: Fuel cell control strategy (a) the air supply system (b) the heat management system [1]

Further, there have been efforts devoted in controlling the reactant flow system in PEMFCs using only voltage and current measurements and inferring power. More specifically, a single-input single-output (SISO) controller between the compressor motor voltage and the delivered current or power to the traction motor. Temperature control in available systems is done using large radiators. As a control mechanism to prevent anode flooding, various ingenious mechatronic solutions have been proposed to abate anode flooding (Rodatz et al., 2002) [?].

2.2 Fuel Cell Control

The Fuel cell consists of a hydrogen supply system, a water and heat management system and an air supply system. The compressed hydrogen is stored in several tanks, under pressures of about 30 MPa. The hydrogen pressure is lowered and kept at a stable

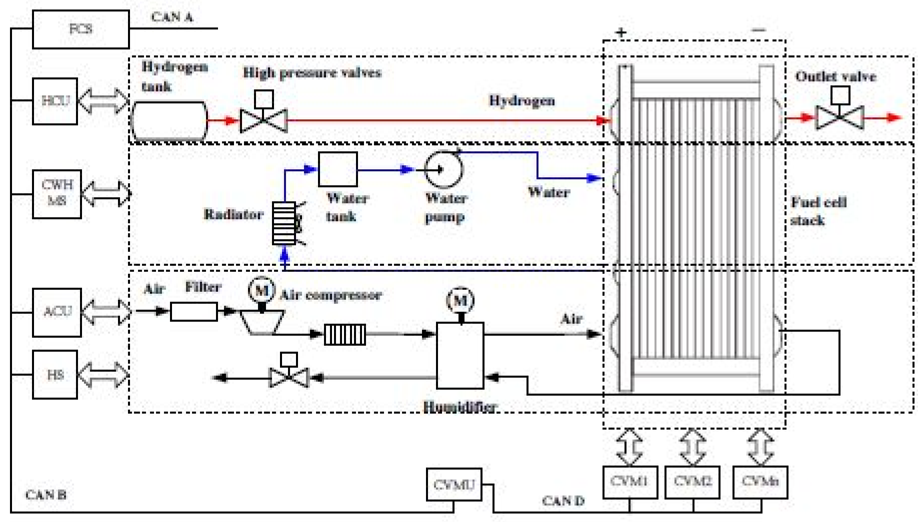

Figure 2.4: Hydrogen Fuel Cell Control [1]

level using several valves for safety purposes before the hydrogen goes into the stack. Water accumulates in the stack due to the electrochemical reaction during the operation of the fuel cell, which leads to performance decay. An outlet valve is installed so that the accumulated water can be blown away with hydrogen. The outlet valve and the hydrogen valves used for lowering and stabilizing the pressure are controlled by the Hydrogen Control Unit (HCU).

The electro-chemical reaction also generates heat, and causes the temperature to increase. The water and heat management system targets to control the stack temperature within a suitable range using deionized water in a water tank. The water flow is controlled by a water pump. The water goes into the stack with a low temperature, and comes out of the stack with a high temperature. A radiator is used to cool the warm water.

The cooling water temperature is measured, and controlled by a feedback control algorithm. The air supply system comprises an air filter, a compressor and a humidifier. The impurities in air will cause the catalyst to be poisoned. Thus as a preventive measure, the air should be filtered before getting into the stack. The air flow is controlled by the compressor with a feed forward + feedback algorithm.

The air is further humified since there should be some water in the PEM, to allow the PEM to conduct protons. In the humidifier, the dry air is humidified with the damp-heat air out of the stack. The air compressor and the humidifier are controlled by the Air Control Unit (ACU) and the Humidifying System (HS).

2.3 Summary

A fuel cell system integrates many components into a power system. These include DC/DC converters, batteries, and ultracapacitors in the system. In cases where the fuel cell is not fed directly with hydrogen, a reformer must be included. Therefore, there are many control loop schemes, the number of which depends on the configuration of the system.

Many control strategies have been proposed in literature, ranging from feed-forward control,Linear quartertic regulator, Neural Networks and Model Predictive Control. A good number of research papers focus on the low level control of the fuel cell to fulfil at least one of the three main objectives such as maximum efficiency, voltage control and/or starvation prevention. However, these designs are still at the theoretical stage and without real time testing. This leads to a methodological gap in the area of hydrogen fuel cell control. The validity of these control strategies for real fuel cell system applications is, however, still under investigation.

Furthermore, the extensive studies in the controller design methods are evidence that the fuel cell system control is a very active research area. The research in this area is mainly motivated by the recognition that the current control methods cannot fully meet the desired design requirements on fuel cell system performance, stability, and robustness etc. Any controller design which gives a satisfactory performance on fuel cell system behavior is worth consideration for implementation [**?**].

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.

Two genral types of models are used in simulation of fuel cell technology, the approaches are detailed lumped parameter dynamic models and black-box models based on system identification. The black box model commonly expresses as NARX (Nonlinear Auto Regressive with eXogenous input) or ARMAX (Auto Regressive Moving Average with eXogenous input) equations. This project 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

Hydrogen is an input variable and is fed at an adjustable flow rate $\mathrm{N_H}$ as well as oxygen expressed as $\mathrm{n_A}$ derived from air. Voltage and current are the system outputs. Franklin et al [**?**], represent this as Multiple Input Multiple Output (MIMO) System as shown in the Figure 3.4 below.

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

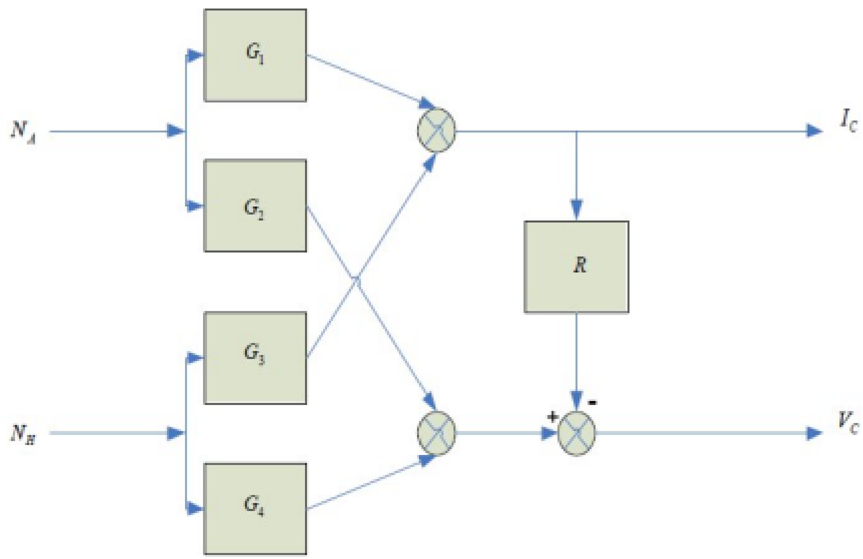

Figure 3.1: MIMO representation of fuel cell [?]

equations:

$$V_c = G_2N_A + G_4N_H + RI_C \tag{3.1}$$

$$I_C = G_1N_A + G_3N_H \tag{3.2}$$

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. A functional motor health monitoring device will be developed and tested.
2. The predictive maintenance algorithm will be formulated and proved from a selection of diverse methods.
3. The controller supporting circuitry will be developed with a custom printed circuit board.
4. Electric motor system performance and efficiency will be optimized using insights from real-time data collected.

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: Work plan table

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