FUZZY LOGIC CONTROL OF BIOHYDROGEN PRODUCTION USING MICROBIAL ELECTROLYSIS CELL (MEC) REACTOR FOR STORAGE APPLICATION

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Field of Study: Process System Engineering and Control

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ABSTRACT

The content of this work presents the implementation of Fuzzy Logic Control (FLC) on a microbial electrolysis cell (MEC) for storage applications. Hydrogen has been touted as one of the potential alternative sources of renewable energy to the depleting fossil fuels. MEC is one of the most extensively studied methods of hydrogen production. One of main advantages of MEC is its ability to utilize organic wastes as the substrates for biohydrogen production. However, the MEC system involves microbial interaction contributes to the system's nonlinear behaviour. Due to its high complexity, a precise process control system must be implemented to ensure the MEC systems could operate in a stable manner. Proportional Integral-Derivative (PID) controller has been one of the pioneer control loop mechanism. However, the conventional PID controller has its drawbacks such as the lacking in its ability to adapt properly in the presence of disturbance within a nonlinear system. Advanced process control mechanism known as FLC can prove to be a better solution to be implemented on a nonlinear system due to its similarity in human-natured thinking. In this research, the FLC is implemented onto the MEC system and its performance is evaluated using several control schemes such as constant setpoints, multiple setpoints tracking, internal disturbance rejection, external disturbance rejection and noise disturbance rejection to ensure a timely readiness of hydrogen storage. Similar evaluations are conducted on Proportional-Integral (PI) and PID controllers as well for comparison purposes. FLC has generally resulted in desirable outcomes over the PI and PID controllers. Integral absolute error (IAE) evaluation shows improvement ranging from 42.3% to 99.4% from PI controller to FLC and 36.2% to 99.4% from PID controller to FLC can be obtained from this study.

Keywords: Fuzzy Logic Control, Nonlinear, Microbial Electrolysis Cell, Fuel Cell, Renewable Energy, Simulink

ABSTRAK

Kandungan dalam hasil kajian ini membentangkan perlaksanaan kawalan logik kabur (FLC) pada sel elektrolisis mikroba (MEC) untuk proses penyimpanan. Gas hidrogen telah diisytiharkan sebagai salah satu sumber tenaga yang boleh diperbaharui yang berpotensi sebagai pilihan kepada bahan api fosil yang semakin berkurangan. MEC merupakan salah satu kaedah yang dikaji secara meluas untuk menghasilkan gas hidrogen. Salah satu kelebihan MEC ialah ia menggunakan bahan buangan organik sebagai sumber untuk penghasilan gas hidrogen. Penghasilan gas hidrogen dalam MEC melibatkan interaksi antara mikroba yang menjadikan proses tersebut tidak lelurus. Disebabkan oleh sifat MEC yang sangat kompleks, satu sistem kawalan proses yang jitu harus dilaksanakan supaya MEC tersebut dapat beroperasi dalam keadaan yang dikehendaki dan terkawal. Pengawal Berkadaran-Kamiran-Terbitan (PID) merupakan salah satu kawalan perintis dalam mekanisme gelung tertutup. Walaubagaimanapun, pengawal PID yang konvensional mempunyai kelemahannya seperti kekurangan untuk menyesuaikan diri dalam keadaan kehadiran gangguan dalam sistem yang tidak lelurus. Satu pengawal proses yang lebih maju yang dikenali sebagai FLC boleh dibuktikan sebagai kaedah penyelesaian yang lebih baik jika dilaksanakan pada sistem yang tidak lelurus disebabkan cara ianya berfungsi seakan mencontohi pemikiran manusia. Di dalam kajian ini, sistem MEC akan dioperasikan dalam kajian kawalan gelung tertutup dengan perlaksanaan FLC pada sistem MEC dan prestasinya akan dinilai melalui pelbagai kaedah kawalan secara berperingkat yang merangkumi titik tujuan yang tetap, penjejakan titik tujuan yang berubah, penolakan gangguan dalaman, penolakan gangguan luaran proses, penolakan gangguan bunyi kebisingan dan model sistem yang tidak sepadan. FLC akan dinilai lagi dengan kebolehannya dalam memastikan kesediaan bekalan gas hidrogen pada masa yang tepat. Cara pengujian yang sama akan dilaksanakan pada pengawal Berkadaran-Kamiran (PI) dan PID untuk tujuan perbandingan. FLC telah menghasilkan hasil kawalan yang lebih baik berbanding dengan pengawal PI dan PID. Penilaian ralat mutlak integral (IAE) menujukkan peningkatan prestasi dalam julat dari 42.3% ke 99.4% dari pengawal PI kepada FLC dan dari 36.2% ke 99.4% dari pengawal PID kepada FLC dapat diperoleh daripada kajian ini.

Kata kunci: Kawalan logik kabur, tidak lelulus, sel elektrolisis mikroba, sel bahan api, tenaga yang boleh diperbaharui, Simulink

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LIST OF ABBREVIATIONS

AC	:	Activated carbon
AEM	:	Anion exchange membrane
BOD	:	Biochemical oxygen demand
BES	:	Bioelectrochemical system
BEAM/MEC	:	Bioelectrochemically assisted microbial reactor
BESF	:	Bromoethanesulfonate
CNT	:	Carbon nanotube
CEM	:	Cation exchange member
COD	:	Chemical oxygen demand
CES	:	Chloroethanesulfonate
DOC	:	Dissolved organic carbon
FLC	:	Fuzzy Logic Control
HER	:	Hydrogen evolution reaction
AHX	:	Hypoxanthine
IAE	:	Integral absolute error
MEC	:	Microbial Electrolysis Cell
MFC	:	Microbial Fuel Cell
MPC	:	Model Predictive Control
NS	:	Neomycin
NN	:	Neural network
PI	:	Proportional-Integral
PID	:	Proportional-Integral-Derivative
RGO	:	Reduced graphene oxide
VFA	:	Volatile fatty acid

LIST OF NOMENCLATURES

ΔG_r	:	Gibbs free energy
E_{eq}	:	Equilibrium voltage
n	:	Number of electrons involved in the reaction
F	:	Faraday's constant
η_E	:	Electrical efficiencies
η_{E+S}	:	Overall energy recoveries
I_V	:	Volumetric current densities
Q/Q_{H_2}	:	Hydrogen production rate
CE	:	Coulombic efficiency
R_{CAT}	:	The cathodic hydrogen recovery
R_{H_2}	:	Overall hydrogen recovery
$p(t)$	:	Controller output
$\bar{p}$	:	Bias (steady state) value
K_c	:	Controller gain
$e(t)$	:	Error signal
τ_I	:	Integral time
τ_d	:	Derivative time
S	:	Concentration of substrate
x_a	:	Concentration of anodophilic microorganism
x_m	:	Concentration of acetoclastic microorganism
x_h	:	Concentration of hydrogentrophic microorganism
M_{ox}	:	Oxidized mediator fraction per electricigenic microorganism
E_{CEF}	:	Counter-electromotive force

η_{act}	:	Activation loss
η_{conc}	:	Concentration loss
η_{ohm}	:	Ohmic loss
$\eta_{conc,A}$	:	Concentration loss at anode
$\eta_{conc,C}$	:	Concentration loss at cathode
i_0	:	Exchange current density in reference conditions
$A_{sur,A}$	:	Anode surface area
β	:	Reduction or oxidation transfer coefficient
I_{MEC}	:	Current of microbial electrolysis cell
R_{int}	:	Internal resistance
R_{min}	:	Lowest observed internal resistance
R_{max}	:	Highest observed internal resistance
K_R	:	Constant to determine the curve steepness
$\mu_{max,m}$	:	The maximum growth rate of the acetoclastic methanogenic microorganism
$\mu_{max,a}$	:	The maximum growth rate of the hydrogenotrophic microorganism
$\mu_{max,h}$	:	The maximum growth rate of the anodophilic microorganism
$q_{max,a}$	:	The maximum reaction rate of the anodophilic microorganism
$q_{max,m}$	:	The maximum reaction rate of the acetoclastic methanogenic microorganism
$K_{S,a}$	:	The half-rate (Monod) constant of the anodophilic microorganism
$K_{S,m}$	:	The half-rate (Monod) constant of the acetoclastic

		methanogenic microorganism
K_M	:	Mediator half-rate constant
K_h	:	Half-rate constant
Y_{H_2}	:	The dimensionless cathode efficiency
Y_h	:	The yield rate for hydrogen consuming methanogenic microorganisms
m	:	The number of electrons transferred per mol of H2
P	:	The anode compartment pressure
E_{app}	:	The electrode potentials
$K_{d,a}$	:	The microbial decay rates of the anodophilic microorganism
$K_{d,m}$	:	The microbial decay rates of the acetoclastic methanogenic microorganism
$K_{d,h}$	:	The microbial decay rates of the hydrogenotrophic microorganism
Y_M	:	The oxidized mediator yield
γ	:	The mediator molar mass
V_r	:	The anodic compartment volume
S_0	:	The initial conditions of organic substrate concentration in the influent and in the anodic compartment
x_{h0}	:	The initial conditions of hydrogenotrophic methanogenic microorganisms
x_{a0}	:	The initial conditions of anodophilic microorganisms
x_{m0}	:	The initial conditions of acetoclastic methanogenic microorganisms

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background

The need for energy has proven to be an essential one as it is required to conduct virtually all human activities. Despite realising the current energy crisis, mankind is still taking energy usage for granted (Chamoun *et al.*, 2015). Speculation arises that fossil fuel reserves could only support a maximum of 40 years for petroleum, 60 years for natural gas and 156 years for coal (Midilli *et al.*, 2005). On another note, the overreliance on fossil fuel as the main source of energy since the First Industrial Revolution has also negatively impacted the environment. The excessive use of fossil fuel has caused global climate change due to the emission of greenhouse pollutants, which leads to formation of compounds such as CO_x, NO_x, SO_x and C_xH_y (Das *et al.*, 2001; Yokoi *et al.*, 2002).

The search for an alternative source of renewable energy has to be conducted extensively in order to replace the depleting fossil fuels. Hydrogen has been touted as one of the best option of alternatives. This fact is supported by various reasons such as hydrogen being the most abundant element in the universe, which makes it a sustainable source. The non-toxic nature of hydrogen makes it an environmentally pleasant source of energy as well. The high energy density of mass basis of hydrogen, which is $120\ MJ\ (33.33\ kWh)$, exceeds double for most type of fuels (Hwang *et al.*, 2014). A more comprehensive value of energy contents of various energy sources can be referred to Table 1.1. Hydrogen could also provide contribution as a major economic growth on a global scale (Mohan *et al.*, 2007).

Table 1.1: Energy contents of selected fuel (World Nuclear Association, 2018)

Fuel	Energy contents (MJ/kg)
Hydrogen	120-142
Methane	50-55
Methanol	22.7
Dimethyl ether	29
Petrol/Gasoline	44-46
Diesel fuel	42-46
Crude oil	42-47
Liquefied Petroleum Gas (LPG)	46-51
Natural Gas	42-55
Firewood (dry)	16

Microbial electrolysis cell (MEC) is a novel process being one of the most extensively studied methods to produce hydrogen gas. One of the main perks of producing hydrogen via MEC is it utilizes biowaste such as fermentable organics and domestic effluents as substrate (Ditzig *et al.*, 2007; Kadier *et al.*, 2014). The conversion of such waste into a product of higher value is in compliance with the waste to energy initiative (Khan *et al.*, 2020).

The contents of this dissertation present on the implementation of fuzzy logic controller (FLC) on a non-linear system like MEC. Data to aid the development of fuzzy logic-based controller are collected based on simulation work of open-loop and closed-loop study on the MEC system. An evaluation of robustness testing is be conducted on the MEC system upon the integration of fuzzy logic, Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers, respectively. This provides a gauge on how well these controllers function properly in the presence of disturbances. The controllers are then assessed accordingly on their readiness to ensure a hydrogen storage system could meet the demand of clients under various control schemes.

1.2 Problem statement

The production of hydrogen via MEC is a nonlinear and highly complex, which is mainly contributed by the multiple microbial interactions. Such complexity of the system makes it difficult to operate and control under desired stable conditions. Conventional PID controller has been one of the pioneer control systems to ensure process stability. However, the nonlinearity of the MEC poses a challenge for the PID controller to play its role to maintain the stability of biohydrogen production due to its narrow operating range (Yahya *et al.*, 2015). In a manufacturing facility of hydrogen gas, it is crucial to ensure a consistent production of hydrogen. This is to anticipate the potential high demand of hydrogen gas an energy source and making sure it is readily available in its repository. A precise and robust control system has to be implemented onto the MEC system with wider operating range. A desired controller should ensure a chemical process to produce output with minimal overshooting and shorter settling time. In addition, it must be able to adapt well and readjust the process back to its designated setpoint in the presence of disturbances.

1.3 Objectives of research

The adoption of an advanced controller by MEC has to be done to address its nonlinear traits, which could ensure a stable production of hydrogen. There are works conducted to evaluate the performance of advanced process control implementation on MEC (Yahya *et al.*, 2015; Yahya *et al.*, 2018). However, the study of leveraging a fuzzy-based controller onto the MEC has yet to be done. The main objective of this study is to evaluate the performance of a fuzzy logic-based controller to regulate the hydrogen production by a MEC system. This subsequently ensures the storage of hydrogen gas to be available on schedule.

The objectives of this study are as follow:

1) To simulate a MEC system to produce biohydrogen for storage purposes.
2) To develop a fuzzy logic controller (FLC) onto the MEC system.
3) To evaluate the performance of FLC against PI and PID controllers upon their implementation onto the MEC system.

The first objective of this work aims to generate a simulation on the production of hydrogen via MEC. An open-loop study is conducted based on the simulation to study what are the graphical behavior and trends of parameters within the system, which contributes to the high complexity of hydrogen production. Based on the collection of initial data from the MEC simulation as guidelines, a fuzzy-based closed-loop controller is constructed to ensure a stable output from the system for hydrogen storage. In order to access the performance of the FLC is gauged against the commonly used conventional PI and PID controllers on various aspects.

1.4 Scopes of work

A literature study present finding on the working principles of bioelectrochemical systems (BESs), namely the MEC and microbial fuel cell (MFC). Further sharing of findings includes various process control techniques that have been implemented on the highly complex BESs. This work then proceeds to develop a fuzzy-based controller to be implemented on the MEC by adopting the mathematical modelling by (Azwar, 2017). The control performance of FLC upon implementation on MEC is compared against the PI and PID controllers. The timely availability of hydrogen repository with the implementation of respective controllers are also assessed in this work.

1.5 Organization of Dissertation

This dissertation is divided into five chapters, where each chapter contains distinctive contents on how this work proceeds progressively.

Chapter 1 presents on the background, problem statement, objective and scopes of this research.

Chapter 2 shares literature findings on the working principles of both MFC and MEC along with the components, which make up the systems. This chapter also shares the control system that has been implemented on the MFC and MEC for performance improvement.

Chapter 3 details on how the works of this research is to be conducted to reach its objectives. Works include development of FLC to be implemented on a non-linear MEC system for hydrogen production. This is then followed by how the performance of FLC is evaluated against the PI and PID controllers via robustness testing, which is to determine how well can the controller adapts to multiple setpoint changes and introduction of various disturbance. There are five robustness testing involve, namely constant setpoint, multiple setpoints tracking, internal disturbance rejection, external disturbance rejection and noise disturbance rejection.

Chapter 4 shares the results obtained from this study, which is the capability of FLC to control the MEC gauge against the conventional PI and PID controllers. Discussions of results include the observation of overshooting and settling time of the controllers against its designated setpoint(s) throughout the simulation. The controllers are also gauged on its capacity to have hydrogen storage system to be timely available.

Chapter 5 concludes the performance of FLC being implemented onto the MEC in general and how it could be an alternative to the conventional PI and PID controllers. A recommendation of future works is also provided as on how this research could improve potentially by FLC implementation.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this section, contents with relevance to this study are presented. This includes literature findings for established research, which provide descriptions on each component involved in a microbial electrolysis cell (MEC) and process control.

This portion begins with the working principle of MEC, which is the process for biohydrogen production from wastewater driven by an external voltage. Descriptions on the role for each component and how they work in synergy to make up the MEC system are elaborated. The components mentioned comprise of the electrodes, membranes and substrates.

The variation of process control systems implemented onto the MEC system are also shared in this section. The conventional Proportional-Integral-Derivative (PID) controller, being the pioneer control system is firstly presented. This is subsequently followed by the elaborations of advanced process control systems such as the neural network, model predictive and fuzzy logic controller, which provide better adaptive alternatives to the conventional PID controller for a stable hydrogen production via MEC.

2.2 Bioelectrochemical Systems

Bioelectrochemical system (BES) is one of the favoured approaches for energy production. BES involves oxidation-reduction at the anode and cathode electrodes, which is catalysed by the microorganisms as electrochemical catalyst. The two notable BES are the MEC and microbial fuel cell (MFC) (Azwar *et al.*, 2014).

2.2.1 Microbial Electrolysis Cell

MEC is designed to produce biogas or chemicals with added value from biowaste (Chookaew *et al.*, 2014; Clauwaert *et al.*, 2007; Logan *et al.*, 2008). The working principle of MEC is such that exoelectrogenic bacteria oxidize the organic matter from substrates. The electrons produced from the oxidation is then transferred to a solid anode electrode while the biowaste is being converted to protons. Upon travelling through an external circuit, the electrons then combine with free protons at an anaerobic cathode to produce hydrogen (Logan *et al.*, 2008). Under ordinary circumstances, it would not be possible to drive the hydrogen evolution reaction (HER) at the cathode due to the insufficient reducing power attainable. However, with the supplementation of a relatively small value of voltage (typically ranging from 0.2 V to 1.0 V), the occurrence of cathodic HER in MEC is possible.

In order to compute whether a chemical reaction shall occur spontaneously, determining the value of Gibbs free energy (ΔG_r) of the process provides an indicative approach. ΔG_r denotes on the tendency of reaction to proceed in a given direction (Cottis *et al.*, 2010). To assure a spontaneous forward reaction, a negative value of ΔG_r has to be obtained. The Gibbs free energy of reaction (ΔG_r°) conversion of acetate to hydrogen in a MEC under standard biological condition (T = 25 °C, P = 1 bar, pH = 7) can be represented as below:

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + H^+ + 4H_2 \quad (2.1)$$

$$(\Delta G_r^\circ = +104.6\ kJ/mol)$$

Where,

CH_3COO^-: $Acetate$
$4H_2O$: $Water$
HCO_3^-: $Bicarbonate$
H^+: $Hydrogen\ ion$

$H_2 : Hydrogen$

The positive value of $\Delta G_r^{\circ\prime}$ indicates that the spontaneous conversion of acetate to hydrogen is not possible. Additional energy needs to be applied to the reaction in order to drive the conversion process forward. The amount of voltage supplied to the MEC to overcome the thermodynamic barrier has to be more than the value of $\Delta G_r^{\circ\prime}/nF$. The value refers to the equilibrium voltage $\left(E_{eq}\right)$, which can be evaluated as the following:

$$E_{eq} = -\frac{\Delta G_r^{\circ\prime}}{nF} = -\frac{104.6 \times 10^3}{8 \times 96485} = -0.14\,V \tag{2.2}$$

Where,

$n = number\ of\ electrons\ involved\ in\ the\ reaction$
$F\ (Faraday\ constant) = 96485\ \ C/mol\ e^-$

The obtained negative value of -0.14 V of the reaction further implies that the hydrogen production could not occur spontaneously and would require external voltage to be applied onto the system. Figure 2.1 shows how biohydrogen is produced via MEC.

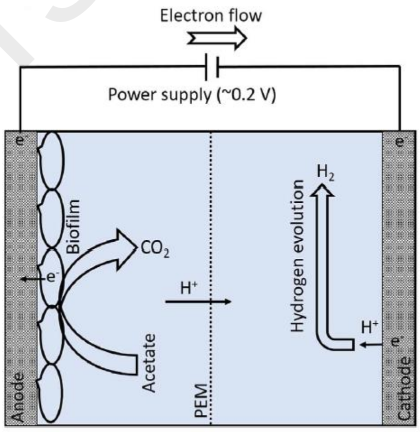


Figure 2.1: Operational principle of MEC with PEM (Karthikeyan *et al.*, 2017)

Producing hydrogen via MEC system exhibits traits of nonlinearity. The great complexity of the system is contributed by interactions of microorganisms present within the fuel cell. A mathematical model was developed by Pinto *et al.* (2011), illustrating the biohydrogen production via MEC. An extension Pinto *et al.* (2011)'s work has been conducted by Yahya *et al.* (2015), which present how microorganisms behave individually throughout the operation of MEC system in a fed-batch configuration through open-loop study.

The anodophilic microorganism resides in the anaerobic biofilm, which mainly plays the role of transferring electrons to the anode (Bond *et al.*, 2002). The same layer of biofilm on the anode also consists of acetoclastic methanogens, contributes to methane production in MEC. While on the cathode, its biofilm is occupied by hydrogenotrophic methanogens (Park *et al.*, 2019). With the observations of all three mentioned microorganisms, it can be observed in Figure 2.2 that competitions exists to feed on the carbon source from the substrates. A plunge in the concentration of acetoclastic microorganism is seen as it consumes the carbon source available for methane and carbon dioxide production. Anodophilic microorganism on the other hand demonstrates a brief increment in concentration, which peaks at Day 2 before declining. Hydrogenotrophic microorganism is shown to have great dominance in consuming the carbon source at the fastest rate.

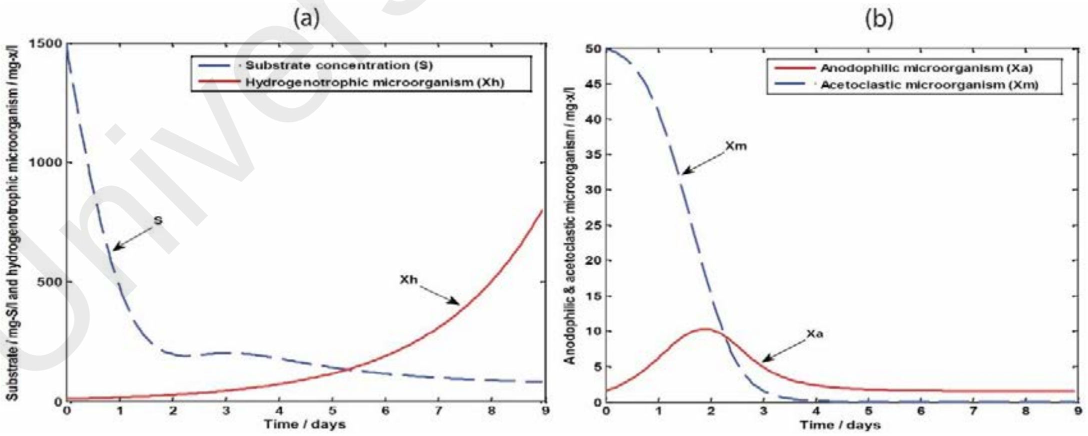


Figure 2.2: (a) Behavior of anodophilic and acetoclastic microorganism within the MEC system & (b) Behavior of substrate concentration and hydrogenotrophic microorganism within the MEC system (Yahya *et al.*, 2015)

2.2.2 Microbial Fuel Cell

MFC differs to the MEC in terms of its configuration that is, its cathode being exposed to air to facilitate oxygen reduction. This then enables electricity generation by MFC (Logan *et al.*, 2006). The bioelectrochemical activities in MFC are very similar to that of MEC with the microorganisms oxidize substrates to produce electrons. The electrons are then being transferred to the anode where it will flow through an external circuit to the cathode to generate electrical current (Liu *et al.*, 2004).

In MFC system with acetic acid as its substrate, the half reactions at the anode and cathode can be represented as follows:

$$\textit{Anode: } CH_3COOH + 2H_2O \rightarrow 2CO_2 + 8H^+ + 8e^- \quad (2.3)$$

$$\textit{Cathode: } 8H^+ + 8e^- \rightarrow 4H_2 \quad (2.4)$$

Hydrogen production at cathode would typically require circuit voltage in the region of 300 to 410 mV in a MFC system. Such approach to produce hydrogen led to significant reduction of input voltage of 1210 mV required by electrolysis of water (Liu *et al.*, 2005). Figure 2.3 exhibits how MFC system generates electricity.

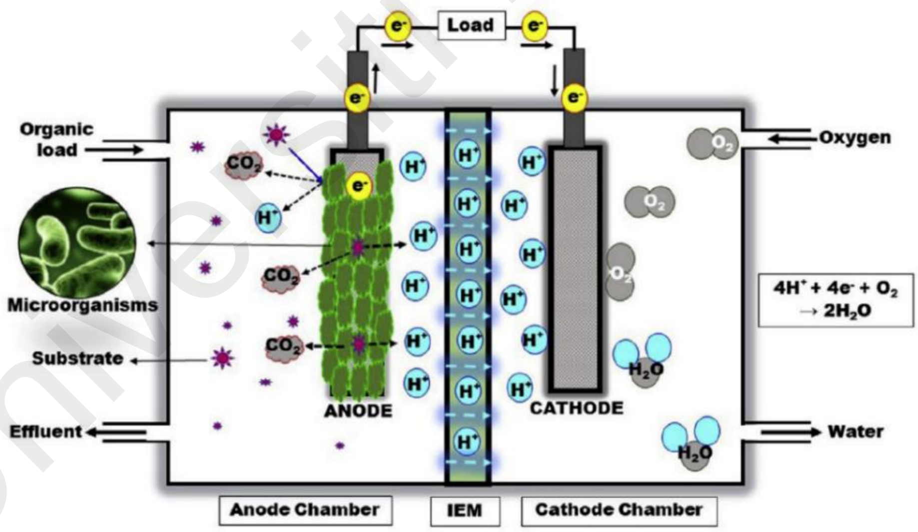


Figure 2.3: Operation of MFC to generate electricity and conduct wastewater treatment process (Palanisamy *et al.*, 2019)

2.3 Components of Bioelectrochemical Systems

Bioelectrochemical systems (BESs) are made up of multiple components for energy production. Each component that makes up the whole of BES uniquely influence the performance of the bioelectrochemical process.

2.3.1 Electrode

One component of BES that plays a role in mainly transferring electrons, which is the electrode has been extensively studied in the past decade to enhance the performances of both MEC and MFC. This involves fabrication of metal-catalyst electrode (Call *et al.*, 2008), platinum, stainless steel (Zhang *et al.*, 2010) and nickel alloy (Selembo *et al.*, 2009).

2.3.1.1 Anode electrode

The optimized production of biohydrogen production via MEC requires anode that possesses features such as excellent electrical conductivity, low toxicity towards microbes, non-corrosive towards substrates or electrolytes, low overpotential, high surface to volume ratio and ease in electrons transfer from microorganism easily (Huang *et al.*, 2008). A study conducted by Li *et al.* (2014) highlighted the importance of microorganism adhesiveness on the anode and electron transfer capability from microbes to electrodes, which could influence the performance of MFC.

Carbon-based electrodes such graphite plates, carbon felt, carbon rods and carbon fibre have been the commonly used anodes for MFC systems. Further heat and acid treatment of carbon-based anode conducted by Feng *et al.* (2010) improves generated power density of MFC from $1{,}020\ mW\ m^{-2}$ to $1{,}370\ mW\ m^{-2}$, which can referred to in Table 2.1.

Table 2.1: Performance of carbon anodes before and after simple heat and acid treatment process (Feng *et al.*, 2010)

	Before treatment	After treatment
Power density (mW m^{-2})	1,020	1,370
Coulombic efficiency (%)	14.6	19.6

The current modification trend of conventional carbon-structured electrode by adopting nanostructured material implementation, has been regarded as a potential anode for MFC. The modification resulted in ohmic loss reduction, coupled with increase in microbial adhesion properties (Palanisamy *et al.*, 2019). Park *et al.* (2014) developed an anode where iron (II, III) oxide (Fe_3O_4) is being attached to carbon nanotubes (CNTs), resulting in power density of $830\, mWm^{-2}$. This development is able to alter the characteristics of CNT with formation of multi-layered networks, leading to higher tendencies of bacterial growth and electron transfer.

Metal-based electrodes such as silver, stainless steel, aluminium, nickel, molybdenum, titanium, gold, and copper possessing higher electrical conductivity with excellent adhesive properties for microbes, have been touted as potential anodes in MFC (Yamashita *et al.*, 2018). A research conducted by Yamashita *et al.* (2018) shows that adoption of molybdenum as anode in MFC, a power density of $1296\, mWm^{-2}$ is generated.

2.3.1.2 Cathode

The cathodic chamber of MEC is the site of hydrogen production via hydrogen evolution reaction (HER). Kundu *et al.* (2013) highlighted that MEC with plain carbon electrodes obstruct fast hydrogen production due to the high overpotential. This issue is addressed by Call *et al.* (2008) with the addition of platinum catalyst on cathode to reduce its overpotential. The MEC is able to produce higher amount of hydrogen at

$3.12 \pm 0.02\, m^3\, H_2\, .reactor\ volume.day^{-1}$. However, the cost of platinum loading onto cathode appears to be costly.

Kim *et al.* (2007) developed a study fabricating nickel powder blended activated carbon (AC) cathode to produce a cathode that is cheaper in cost. Various nickel powder loadings $(4.8, 19, 46\, mg\, cm^{-2})$ with AC were fabricated in order to study the outcomes of hydrogen recovery. The performance of these nickel powder blended AC cathodes then is being compared to nickel without AC $(77\, mg\, cm^{-2})$. A graphical representation of the research can be referred to Figure 2.4.

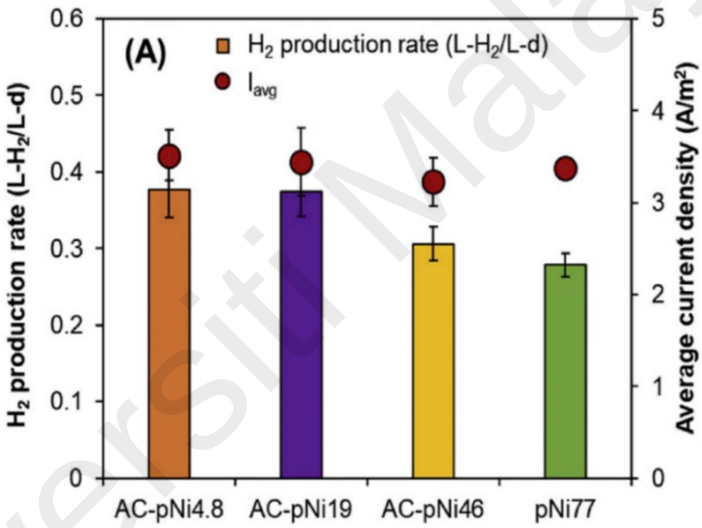


Figure 2.4: The rate of Hydrogen production (L-H_2 $L^{-1}d^{-1}$) along with average current densities produced (A m^{-2}) of MECs with AC-pNi and nickel powder only electrodes (Kim *et al.*, 2019)

It can be interpreted that the cathode with the lowest nickel powder loading results in the highest hydrogen production rate as compared to nickel (Ni) powder only electrode. One of the reasons contributing to such outcome is the excellent electrical conductivity property of AC. This trait of AC improves the electrical connections in the cathode, which leads to the alteration of the cathode's permeability relative to both ion transport and gas evolution (Ivanov *et al.*, 2017). The large particles size of AC $(4 - 30\, \mu m)$ is able to attain a greater surface area exposed to Ni powder particles $(0.5 - 1\, \mu m)$ to the solution. This subsequently impacts the way the binder interacts with the catalysts for the hydrogen evolution reaction (HER). This validates that the porosity and three-dimensional structure of the AC aids in the greater hydrogen production rate (Selembo *et al.*, 2010).

The development of bio-cathodes to be implemented in MEC has been studied extensively recently due to its low fabrication cost and high operational sustainability, which is contributed by its regenerative ability (Jeremiasse *et al.*, 2012; Karthikeyan *et al.*, 2017). A research has been conducted by Jafary *et al.* (2015) to develop an alternative cathode as a countermeasure step to the expensive catalysed cathode known as the bio-cathode. The outcome of the study managed to conclude that hydrogen production in the bio-cathode MEC has been increased by a factor of 6 as compared to the non-inoculated cathode MEC. This is despite that the hydrogen production using bio-cathode being 2.6 times lesser than a Pt-cathode MEC.

2.3.2 Usage of membrane

The utilization of membrane in a MEC system is to facilitate compensation of electrons that has moved from anode to the cathode. The ions will move through an ion exchange membrane (Ter Heijne *et al.*, 2006).

2.3.2.1 Ion exchange membrane

The early development and most common configuration of MEC uses an ion exchange membrane. The working principle of MEC involves microbes in substrate at the anolyte being oxidized, producing electrons to be transferred to the cathode through an external electrical circuit, which eventually reduce the protons to hydrogen gas. The ion exchange membrane minimizes the mixing of hydrogen gas produced at cathode and the microbe at anolyte (Logan *et al.*, 2008). The ion exchange membrane also plays a role to compensate for the negatively charged electrons moving from anode to cathode by allowing ions to move through it.

2.3.2.2 Cation exchange membrane

The first ever ion exchange membrane used in a MEC is the cation exchange membrane (CEM), which is the Nafion 117 (Ion Power Inc., NewCastle, Delaware). The MEC with a CEM configuration operates in a way that the driving force of the protons from anolyte to catholyte is the concentration of cations at the cathode. However, due to the presence of cations such as Na^{+}, NH^{+}, K^{+} and Ca^{2+}, which is 10 times more concentrated than protons in wastewater, the protons that are reduced at the cathode are not replenished by the protons produced at the anode (Gil *et al.*, 2003). Such phenomenon then leads to an increase in pH of the cathode and simultaneously, a decrease in pH of the anode. A computation with the Nernst equation, which computes the electrochemical dynamics in MEC verifies that such change in pH of both electrodes results in loss of voltage as reported by Liu *et al.* (2004).

2.3.2.3 Anion exchange membrane

The replacement of CEM with an anion exchange membrane (AEM) in MEC has resulted in a better performance of biohydrogen production (Cheng *et al.*, 2007). Transportation of anion buffers such as phosphate (PO_4^{3-}) and bicarbonate (HCO_3^{-}) can be used in MEC with an AEM configuration. Such transportation aids in buffering the change in pH of both electrode chambers (Kim *et al.*, 2007). Sleutels *et al.* (2009)'s study follows up from the performance comparison of both CEM and AEM in MEC. The comparison produced an outcome, which hydrogen production of $2.1\, m^3 H_2\, m^{-3}\, d^{-1}$ via AEM configuration being higher as compared to CEM configuration of $0.4\, m^3\, H_2\, m^{-3}\, d^{-1}$. Further comparison between CEM and AEM shows that CEM has an ion transport resistance of $48\, m\Omega\, m^2$, which is higher than AEM of $12\, m\Omega\, m^2$.

Figure 2.5(A) depicts the development of a pH gradient over the membrane due to presence other ions beside the hydroxyl and protons in the electrolyte. Figure 2.5(B) then shows superior current density of MEC system by AEM configuration over CEM configuration in a MEC system.

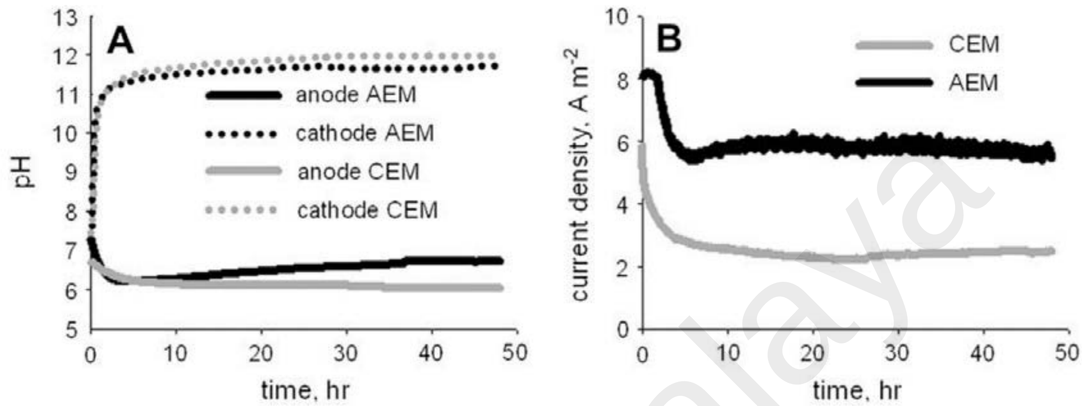


Figure 2.5: Changing of pH (A) in anode and cathode along with current density (B) in MECs equipped with AEM and CEM (Sleutels *et al.*, 2009)

2.3.2.4 Single-chamber membrane-less MEC

The design of MEC can be constructed in the absence of membrane, which can be seen in Figure 2.6. The main advantage of having a true single-chamber architecture in a MEC is the reduction in capital cost (Call *et al.*, 2008; Hu *et al.*, 2008). The removal of membrane would also reduce both the ohmic resistance and bulk pH gradient in the liquid. However, such configuration does not come without a drawback. Due to the absence of membrane in a MEC system, the separation of the 2 electrode chambers would not be possible (Logan *et al.*, 2008). This leads to the occurrence of anaerobic methanogenesis, which is the production of methane as hydrogen produced are being consumed by methanogens on the cathode or in the substrate (Hu *et al.*, 2008). In the presence of acetate and hydrogen in substrates, acetoclastic methanogens prompt the conversion of acetate to methane. Simultaneously, another methanogenesis occurrence is possible with the conversion of carbon dioxide and hydrogen to methane by hydrogenotrophic methanogens (Chae *et al.*, 2010; Wang *et al.*, 2009). All mentioned reactions are represented by the following equations:

Co-production of methanogens,

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (2.4)$$

$$H_2 + CO_2 \rightarrow CH_4 + 2H_2O \quad (2.5)$$

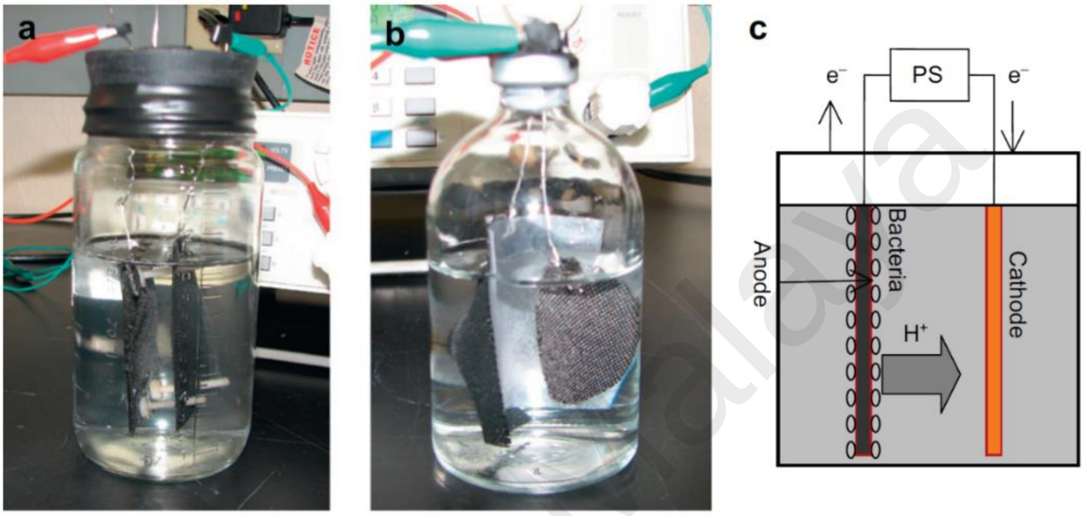


Figure 2.6: Photographs (a, b) and schematic (c) of single-chamber membrane-free MECs (Hu *et al.*, 2008)

An attempt to overcome methanogenesis was conducted by Call *et al.* (2008) by developing a single-chamber membrane free MEC where the cathode is placed in close proximity to the anode. The configuration managed to produce maximum hydrogen production of 3.12 $m^3 H_2 . m^{-3}\ reactor\ volume. day^{-1}$ coupled with minimal methane gas of $1.9 \pm 1.3\%$ in the effluent gas on an average basis. Table 2.2 depicts the outcomes of various membrane configurations in a MEC.

Table 2.2: Electrical Efficiencies, Overall Energy Recoveries, Volumetric Current Densities, and Hydrogen Production Rates as studied by Call *et al.* (2008)

Reactor system	$E_{ap}(V)$	$\eta_E(V)$	$\eta_{E+S}(\%)$	$I_V(A/m^3)$	$Q(m^3/m^3d)$
Gas diffusion membrane electrode	1	148	23	28	0.33
No membrane with brush anode	0.8	194	75	292	3.12
No membrane with brush anode	0.6	254	80	186	1.99
AEM with granule anode	0.6	261	82	99	1.1

Table 2.2: Electrical Efficiencies, Overall Energy Recoveries, Volumetric Current Densities, and Hydrogen Production Rates as studied by Call *et al.* (2008), continued

Reactor system	$E_{ap}(V)$	$\eta_E(V)$	$\eta_{E+S}(\%)$	$I_V(A/m^3)$	$Q(m^3/m^3d)$
Nafion membrane	0.5	169	53	2.8	0.02
No membrane with brush anode	0.4	351	86	103	1.02

The potential of antibiotics such as hypoxanthine (AHX), bromoethanesulfonate (BESF), chloroethanesulfonate (CES) and neomycin (NS) as methanogenesis inhibitor was reported by (Chiu *et al.*, 2001; Moore *et al.*, 2005). Catal *et al.* (2015) then investigate for possible agent to suppress methanogenesis in MEC. The mentioned antibiotics have been studied on their inhibition properties. The MEC is being configured in a manner where the biogas produced is sampled in serum vial and then being released using an air-tight 1 mL glass container. The composition of the sampled biogas is analysed via gas chromatography equipped with a thermal conductivity conductor. The argon is be utilized as the carrier gas inside the column of the gas chromatograph (Hu *et al.*, 2008). The methanogenesis suppression properties of the mentioned antibiotics have been tabulated in Table 2.3.

Table 2.3: Outcome of MECs in the presence of various antibiotics as methanogenesis inhibitor along with 10 mM of sodium acetate (Catal *et al.*, 2015)

Applied voltage (V)	Antibiotic	Current density	CE (%)	R_{CAT} (%)	R_{H2} (%)
0.4	n.a.	2.0	77	20	16
0.7	n.a.	2.5	92	58	53
0.7	NS	2.1	59	31	18
0.7	BES	2.4	36	72	26
0.7	CES	2.4	33	69	23
0.7	AHX	3.9	63	30	19

CE: Coulombic efficiency.
R_{CAT}: The cathodic hydrogen recovery.
R_{H2}: Overall hydrogen recovery.
n.a.: Not applied.

The outcomes in Table 2.3 demonstrate that each antibiotic has its own distinct methanogenesis properties due to unique chemical structures.

2.3.3 Types of Substrate

Both MEC and MFC are novel technologies with prospects to be the state-of-the-art approaches for renewable energy source. What makes them to be promising is that they utilizes various wastes such as organic matter and wastewater as their feed for hydrogen production (Logan *et al.*, 2008).

2.3.3.1 Fermentable Organics

Dark fermentation is one of the favoured methods of hydrogen production. A study conducted by Lee *et al.* (2010) concluded that the rate of hydrogen production for dark fermentation is higher that most similar biotechnological processes. Volatile fatty acids (VFAs) are the main organic pollutants present in the effluent of dark fermentation. A treatment to the VFA has to be conducted before being discharged into the environment. Bioelectrochemical system (BES) is one of the most favoured solutions to treat VFA as it is also capable to generate product of value (Dhar *et al.*, 2015).

Hydrogen is produced from the bacterial fermentation of generally sugars. However due to incomplete conversion, the fermentation process produces by-products such as acetate, butyrate, formate, ethanol and lactate. Nevertheless, these compounds can still further react to produce hydrogen gas. A comparison between a combination of MEC with ethanol dark-fermentation reactor against a MEC with fermentation reactor is depicted in Table 2.4.

Table 2.4: Comparison between combination of a MEC with ethanol dark-fermentation reactor and a MEC with fermentation reactor (Lu *et al.*, 2009)

	MEC and ethanol-type dark fermentation reactor	MEC and dark fermentation reactor
Overall hydrogen produced (m^3d^{-1})	1.41	2.11 m^3d^{-1}
Overall hydrogen recovery (%)	83	70 to 94
Applied voltage (V)	0.6	0.5 − 0.8

Fermentable organics such as the lignocellulosic biomass, which are mainly made of plant dry matter is well-known for its abundancy as an agricultural waste. This fact makes it a cost-effective solution for hydrogen production in MEC. However, due to the complexity of its structure, the lignocellulosic biomass has to be converted into its simpler form such as monosaccharides or compounds with relatively lower molecular weight (Kadier *et al.*, 2014).

Due to the recalcitrant behaviour of lignocellulosic materials, a two-stage dark fermentation followed by an electrohydrogenesis process is required to produce high yield of hydrogen gas. Lalaurette *et al.* (2009) conducted such experiment using a cell culture known as *Clostridium thermocellum* in the dark fermentation process. Its effluent is then fed into a MEC for conduct the electrohydrogenesis process. The substrates used in the two-stage process are corn stover lignocellulose and cellobiose with their respective amount of biohydrogen produced is summarized in Table 2.5.

Table 2.5: Hydrogen produced from two-stage dark fermentation and electrohydrogenesis process (Lalaurette *et al.*, 2009)

Stage	**One**	**Two**
Effluent	**(Dark Fermentation)**	**(Electrohydrogenesis)**
Corn Stover Lignocellulose	$0.25\ L\ H_2L^{-1}d^{-1}$	$1.00\ \pm 0.19\ L\ H_2L^{-1}d^{-1}$
Cellobiose	$1.65\ L\ H_2L^{-1}d^{-1}$	$0.96\ \pm 0.16\ L\ H_2L^{-1}d^{-1}$

2.3.3.2 Domestic Wastewater

Discharged wastewater from domestic usage is another exemplification of a substrate for hydrogen production in MEC. A modification to a typical MEC known as bioelectrochemically assisted microbial reactor (BEAM/MEC) was examined by Ditzig *et al.* (2007) as an evaluation for the system. Besides producing hydrogen gas, BEAM/MEC simultaneously treats the domestic wastewater in order to reduce the values of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and dissolved organic carbon (DOC). By using domestic wastewater with COD of more than $360\ mg\ L^{-1}$ as a substrate, a Coulombic efficiency of 26% is achieved with applied voltage of $0.41\ V$. Using the same substrate, up to 42% of hydrogen is successfully recovered with an applied voltage of $0.5\ V$. The hybrid system also managed to reduce the level of COD, BOD and DOC at an efficiency of $87 - 100\%$. The photograph in Figure 2.7 displays the BEAM/MEC.

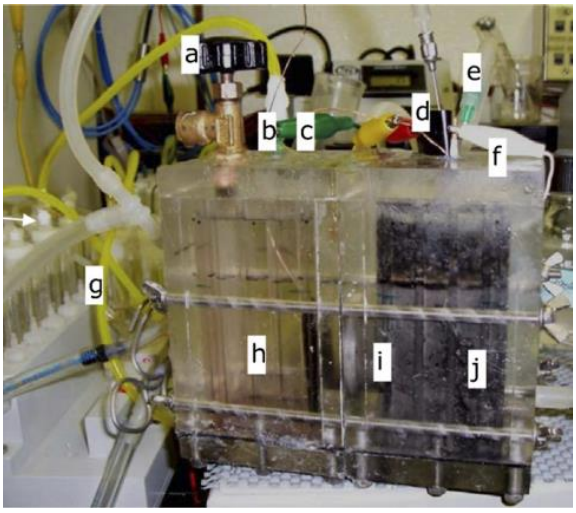


Figure 2.7: Two-chambered acrylic BEAM/MEC reactor shown with the anode chamber filled with granules. (a) Tube to respirometer, (b) headspace sampling valve, (c) wire to anode, (d) wire to cathode, (e) nitrogen sparge, (f) reference electrode, (g) bubble meters, (h) cathode chamber, (i) Nafion membrane, (j) anode chamber (Ditzig *et al.*, 2007)

2.4 Process Control in Biochemical Processes

In recent advancement of chemical process, they are still bounded by various natural and manmade constraints. Such constraints are mainly comprised of stricter environmental regulations, safety of chemical process operation and efficient plant operation. In light of acknowledging the mentioned constraints, it is only natural that the need to understand the process dynamics and process control be crucial (Seborg *et al.*, 2010).

Process control system was first introduced in the early 1950s. At this early phase, there was an ongoing discussion on the economic performance to implement process control by using computers (Stout *et al.*, 1995). There are various successes on installations of process control system, which leads to significant economic benefits (Eliot *et al.*, 1962). Thus, in 1960s there is an apparent linear growth in the number of process control computers being applied in chemical and petroleum plants. Further convincing results were shown in 1970s, which shows that implementation of process control could ensure a profitability increment (Martin, 2006). This prompted most manufacturing companies to switch to the new computer technology. Moving forward to

1980s, control systems suppliers such as Setpoint Inc. (Latour, 1976), Profimatics Inc. (Lane, 1968), The Foxboro Company (Martin, 2006) and Honeywell (Tolfo, 1983) have been pitching on their respective products' superiority. As the early 1990s arrives, the pressure of globalization has begun mounting on manufacturing companies to reduce their cost while elevating their productivity (Shunta, 1997). Aronson *et al.* (1990) reported that new generation of distributed control systems (DCS) was developed to ease the implementation of control strategies.

2.4.1 Control Strategies of Bioelectrochemical Systems

In order to ensure a stable hydrogen production via MEC, a proper control strategy has to be established. Yahya *et al.* (2015) conducted a dynamic study on mathematical model developed by Pinto *et al.* (2011), which represents the MEC system. From the open-loop dynamic study, it is evident that the internal parameters have significant impact on the rate of hydrogen production with are closely related to the electrode potential and internal current being applied to the MEC. Furthermore, both electrode potential and internal current exhibit a close relationship. In the implementation of a closed-loop study, Yahya *et al.* (2015) has then selected electrode potential as the manipulated variable to control the rate of hydrogen production.

A modification to the MEC, which is known as MFC generates voltage as the output. A process control study has been conducted by Yan *et al.* (2013) to ensure a stable voltage output from MFC. The flow rate of fuel feed to anode was selected as the manipulated variable to ensure a desired voltage output from the MFC.

2.4.2 Proportional-Integral-Derivative Controller

The implementation of a Proportional-Integral-Derivatives (PID) controller has been regarded as one of the most commonly used feedback controllers. Its applications vary in many engineering sectors such as industrial process and process instrumentation

(Moradi, 2002). PID controllers are being favoured due to their robustness and simplicity when it is being implemented (Wang *et al.*, 2005). The control for a conventional PID controller can be represented mathematically as follows (Seborg *et al.*, 2010):

$$p(t) = \bar{p} + K_c\left(e(t) + \frac{1}{\tau_I}\int_0^t e(t)dt + \tau_d \frac{d}{dt}e(t)\right) \tag{2.6}$$

Where,

$p(t) = controller\ output$
$\bar{p} = bias\ (steady - state)\ value$
$K_c = controller\ gain$
$e(t) = error\ signal$
$\tau_I = integral\ time$
$\tau_d = derivative\ time$

However, conventional PID controller has its shortcomings such as poor tuning capability. It requires repeated trials of tuning in order to avoid potential instability during the tuning and modelling experimental processes (Shamsuzzoha *et al.*, 2010). The other notable disadvantage of conventional PID controller is its slow adaptability when external disturbances are affecting the system it is being implemented on (Guzman *et al.*, 2008).

2.4.3 Advanced Control System

Most chemical processes tend to operate in a nonlinear behaviour at a certain extent. Such dynamic nature could pose a challenge to conventional PID controller, which could only operate at a linear range. To address issue of such, further development of process control system has to be executed as a countermeasure action. The introduction of advanced control methodology such as neural network, model predictive and fuzzy logic controller have proven to ensure the stability of processes with high complexity (Seborg *et al.*, 2010).

2.4.3.1 Neural Network Controller

Most chemical processes, which exhibit sophisticated behavior require significant amount of time and effort develop theoretical dynamic model to ensure a process control system could be implemented. Neural network (NN) controller was inspired by the abilities of human brain to conduct computation at a very high speed. This computation involves interconnected neurons to perform computations such as pattern recognition and perception, which are familiar to the human brain. NN controller then provides an alternative approach to implement a control system onto a chemical process empirically. This alternative would require previous experimental data to establish the empirical nonlinear model (Seborg *et al.*, 2010). The adoption of NN controller then eliminates the need to develop complicated mathematical models Figure 2.8 shows how a typical architecture of an artificial neural network with the input, hidden and output layers.

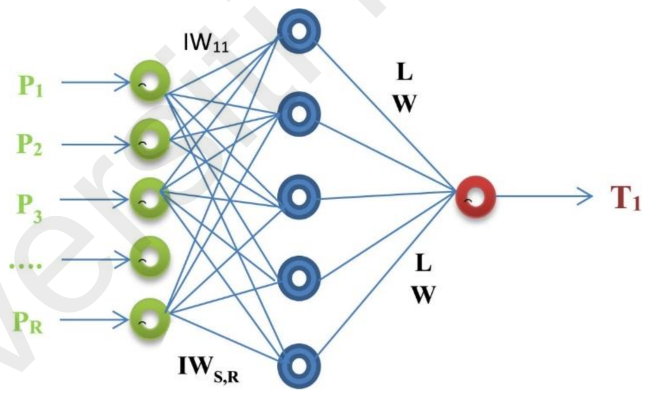


Figure 2.8: A diagram of an artificial neural network where Input layer (green), hidden layer (blue), output layer (red), along with the edges (Ahmadi *et al.*, 2020)

A recent work has been conducted by Yahya *et al.* (2018) to implement an artificial neural network (ANN) based controller on the MEC system. The architecture of the ANN controller that was implemented can be referred to Figure 2.9.

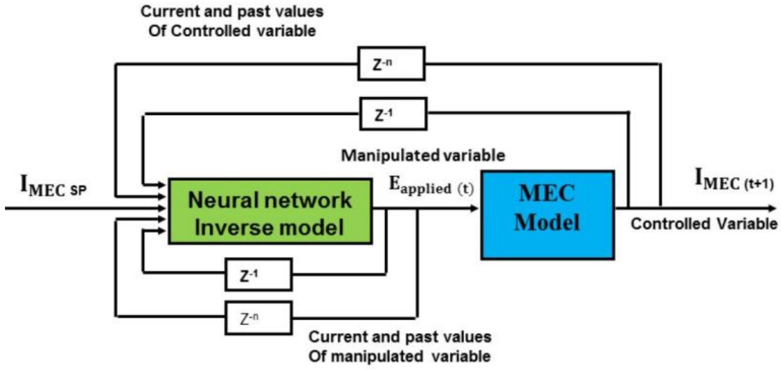


Figure 2.9: The block diagram of the implementation of neural network inverse-based model onto the MEC system (Yahya *et al.*, 2018)

Figure 2.10 depicts a clearer description of the architecture within the neural network inverse-based based model. The input layer consists of multiple parameters at 2 different timestamps are being fed into the hidden layer of neural network. The hidden layer then computes the received data and generated corresponding output to be fed into the MEC system.

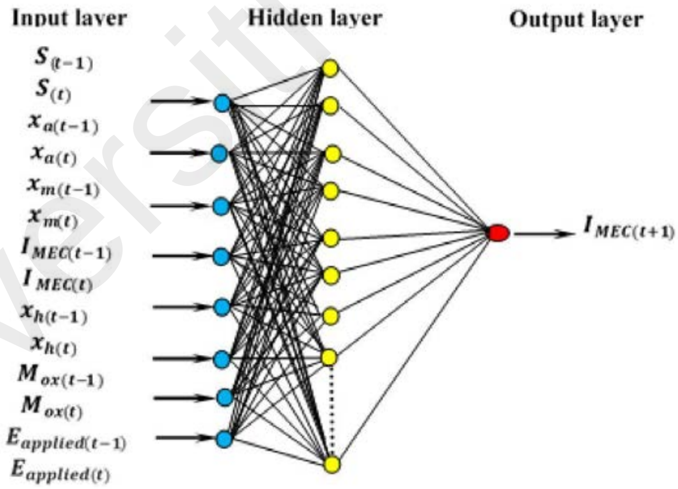


Figure 2.10: The inverse model architecture for the MEC system (Yahya *et al.*, 2018)

The judgment of the controller selection by Yahya *et al.* (2018) is to adopt its capability to control a nonlinear system such as MEC. The ANN based controller resulted in a preferable outcome over the conventional PID due to its faster response time and minimal overshoots coupled with the least offset error.

2.4.3.2 Model Predictive Control

The principle of model predictive control (MPC) enables a system to predict future control action with current input and output variables along with future control signals. It is occasionally adopted as the preferred control methodology due to its algorithm simplicity (Kumar *et al.*, 2012). MPC uses model explicitly to compute predictive output of a system within a future time horizon (Orukpe, 2012). MPC has been widely selected as the option to deal with biochemical process that generally exhibit non-linearity (Ashoori *et al.*, 2009; Fan *et al.*, 2015). Figure 2.11 provides a representation on the algorithm of MPC.

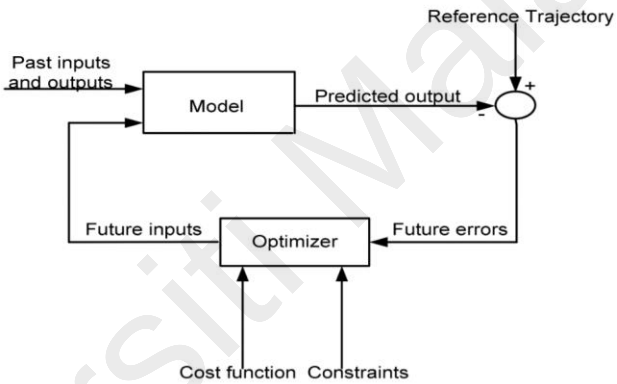


Figure 2.11: Structure of model predictive control (Orukpe, 2012)

Fan *et al.* (2015) developed a control mechanism to ensure a stable voltage output from MFC via MPC. Three different methods are adopted to establish the MPC, which are namely the traditional MPC, improved MPC with Laguerre functions and improved MPC with exponential data weighing. The outcome of the study has concluded that with the adoption of the appropriate MPC, the MFC has resulted in fast response characteristic coupled with steady-state behavior and great robustness.

2.4.3.3 Fuzzy Logic Controller

Fuzzy logic controller (FLC) offers greater attainable advantages in comparison to the conventional PID controller. It emphasizes on fixed and approximate reasoning in contrast to fixed and exact reasoning. The introduction of fuzzy logic was marked with the introduction of fuzzy set theory by Zadeh (1965). The implementation of FLC can express the amount of ambiguity in human-natured thinking, which provides great robustness, model-free and universal approximation theorem (Galzina *et al.*, 2008; Poursamad *et al.*, 2008). Fuzzy theory has a mechanism with the representation of linguistic constructs such as "*many*", "*low*", "*medium*", "*often*" and "*few*" unlike Boolean logic (Cheung *et al.*, 1996). Fuzzy logic controller is evidently more capable to be implemented on a nonlinear process than the PID controller (Stanke *et al.*, 2014).

The detailed operation of FLC can be referred to Figure 2.12. Upon receiving inputs, the fuzzification block firstly converts them into suitable defined fuzzy sets. The inference mechanism (Tiong *et al.*, 2016) then conducts evaluation and combines membership functions with defined fuzzy rule base to determine the fuzzy output. Finally, the output is translated into a term of real value by the defuzzification block (Lee, 1990; Passino *et al.*, 1998).

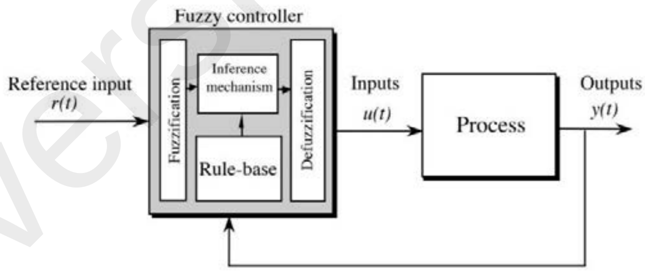


Figure 2.12: Configuration of a FLC (Passino *et al.*, 1998)

Yan *et al.* (2013) conducted a study to integrate fuzzy control on a PID controller for MFC system. Such configuration allows great precision of PID control with the agility and adaptability of a fuzzy controller. The research has resulted in a significant reduction time taken for the MFC to reach its setpoint when PID controller adopts fuzzy logic traits. The integration also sees decrease in the percentage of overshoot.

The application of fuzzy-based controller extends to other highly complex biochemical process as well. To address the issue of nonlinearity of biological approach of wastewater treatment, Bououden *et al.* (2015) implemented a controller based on Takagi-Sugeno fuzzy models. The aim of this study is to ensure a fixed level of pollution at the outlet of the treatment system. The Takagi-Sugeno based controller identifies the nonlinearities within the biological treatment process, which are attributed to the substrate consummation rate. The implementation has then resulted in output of effluent that is insensitive to the variation of influent and presence of noise due to the adaptive mechanism of the fuzzy-based controller.

A common biochemical process known as fermentation has wide range of application in the development of biotechnologies. Much like other similar biochemical processes, the complicated kinetics and various time-varying parameters contribute to the nonlinear dynamics of the fermentation process. The concentration of dissolved oxygen inside a fermenter is a crucial parameter that has to be well-controlled in fermentation of baker's yeast. Vasičkaninová *et al.* (2017) then designed a fuzzy-based controller to ensure a desired profile of oxygen concentration by regulating the gas phase dilution rate periodically. Comparison of control performances on the fermenter between conventional Proportional-Integral (PI) controller and fuzzy-adaptive PI controller has been conducted. The fuzzy-based PI controller produced a preferred outcome attributed by its superior setpoints tracking and better disturbance rejection throughout the fermentation process. Table 2.6 presents established studies on implementation of advanced control system on various biochemical processes with high complexity.

Table 2.6: Selected biochemical processes with implementation of advanced control system

Control Methodology	Biochemical Process	Reference
Neural network controller	Fermentation of Saccharomyces cerevisiae to produce ethanol.	Bulsari *et al.* (1994)
Neural network model based predictive control	Fed-batch cultivation of E. coli BL21 (DE3) [pET3a-ifnγ]	Nikfetrat *et al.* (2009)
Neural network model based predictive control	Continuous fermentation of yeast inside bioreactor for ethanol production.	Nagy 2007
Model predictive control	Continuous sterilization on biological medium before fermentation.	Zhang *et al.* (2016)
Fuzzy logic controller	Fermentation of Coenzyme Q_{10}.	Yamada *et al.* (1991)
Fuzzy logic controller	Maximize glutathione production in yeast fed-batch culture.	Alfafara *et al.* (1993)
Fuzzy logic controller	Improvement of cloned α-amylase gene expression in fed-batch culture.	Shiba *et al.* (1994)
Takagi-Sugeno fuzzy control	Biological wastewater treatment in pulp and paper industry via continuous-flow aerated bioreactor.	Grisales *et al.* (2006)

As of the current extent of research, much study is still being conducted to ensure the optimised production of hydrogen via MEC. This is conducted by analysing each component involved in MEC, which includes electrodes, membrane, substrates and process control system to be implemented.

2.5 Summary of Chapter

The prospect of developing BESs that generate energy from waste remains extensively studied. The BESs comes in the form on MEC and MFC, which produces hydrogen and electricity, respectively.

Enhancing the performance of BES could be conducted via modification of the components making up the system. Firstly, various electrodes have unique characteristics to provide alteration of their electro-conductivities within the BES. Membranes has a pivotal role to regulate the concentration of ions within the anodic and cathodic chambers of the BES. In addition, the components within substrates affects the amount of output from the system.

Due to the highly complex dynamic in the working principles of both BESs, which are mainly contributed by various microbial interactions, precise controllers have to be implemented to ensure a stable operation of BESs. Various literature studies have been conducted to determine the suitable control strategies for both MEC and MFC. Electrode potential is the most suitable parameter to be regulated to ensure a stable hydrogen production within the MEC. The flow rate of fuel feed to anode on the other hand, would be the appropriate manipulated variable to control voltage output from MFC system.

In terms controller adoption, conventional Proportional-Integral-Derivative (PID) controller has been one of the pioneer selections to serve such purposes. However, the limited operating range of the PID controller may not be suitable on a non-linear chemical process. The implementation of advanced process controller such as artificial neural network, model predictive and fuzzy logic controllers provide better alternatives as these controllers adopt adaptive capability to ensure a complex chemical process to operate steadily.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The design of hydrogen production system, which comprises the source of hydrogen gas and storage tanks for repository purposes has to take various aspects into consideration. One of the key elements is to ensure the whole production system operates in stable manner. Fulfilment of such criteria could ensure the readiness of hydrogen storage system in a timely manner thus, satisfying the needs and expectations of client. A well-controlled environment of the microbial electrolysis cell (MEC) for hydrogen production could also aid in ensuring a safe working condition in compliance to regulations. Hence, the adoption of process controller is brought in to address this aspect.

In this chapter, a step-by-step methodology on how the operation of MEC system is conducted. Existing mathematical modelling for the MEC system is from literature studies. The existing models depicting the mass balances and electrochemical process are modified based on the actual experimental work conducted.

This is then followed by the design of the control methodology, which is implemented onto the MEC system. This includes the definition of fuzzy logic rules on the fuzzy logic controller (FLC). Then, the scheme on how the control system is conducted and evaluated is also presented. A schematic illustration for the simulation of MEC system can be referred to Figure 3.1.

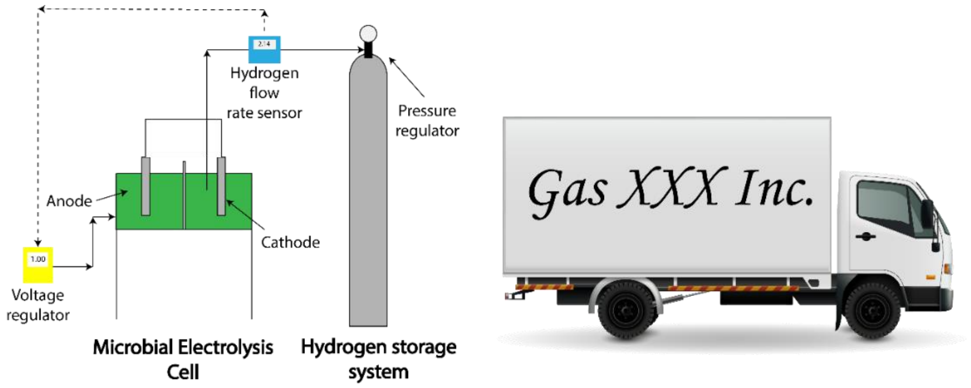


Figure 3.1: Schematic diagram on hydrogen production via MEC and storing the hydrogen produced in a storage tank for delivery purposes

The flow rate of hydrogen produced from the MEC is constantly monitored. In the event, where discrepancy occur between the current hydrogen flow rate reading and the setpoint, rectification work is conducted by the voltage regulator to ensure the flow rate returns to its designated value. A hydrogen storage system highlighted by Johnson *et al.* (2011) consists of nine 37.4 L cylindrical tanks, which can be seen in Figure 3.2. Similar storage system is adopted with simplifications to accommodate the hydrogen production capacity of the MEC. The simplifying of the storage system is discussed in the later part of this chapter.

Figure 3.2: Hydrogen storage system with nine, DOT 3A cylindrical tanks (Johnson *et al.*, 2011)

The flowchart in Figure 3.3 depicts the progressive approach to conduct this work. Firstly, the development of mathematical model representing the MEC system is conducted. Upon adoption of the model, the MEC is simulated via Simulink. Next, the simulated MEC is validated via open-loop studies against available mean of published literature in terms of trend and correlation. The closed-loop controllers that are implemented onto the MEC, which includes Proportional-Integral (PI), Proportional-Integral-Derivative (PID) and fuzzy logic controllers are designed. Finally, the performance of the implemented controllers onto the MEC are then evaluated and analysed.

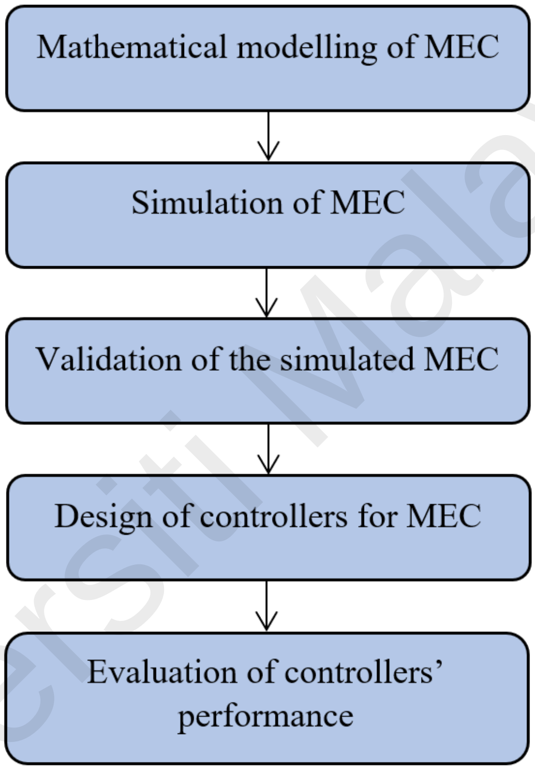


Figure 3.3: Flowchart on the methodology of this work

3.2 Mathematical Modelling

The following mathematical model is based on multi-population MEC model developed by Pinto *et al.* (2011). Yahya *et al.* (2018) has suggested a few modifications in this case study such as:

1. The model is modified into a fed-batch reactor. The Pinto model uses a continuous system configuration.
2. The biofilm formation and retention shall only consist of two-phase model biofilm growth, which are the anodic biofilms (Layer 1) and a cathode biofilm

population (Layer 2). The Pinto model uses three phases, an outer biofilm layer (Layer 1), an inner biofilm (Layer 2) and cathode biofilms (Layer 3). The justification of utilizing the two-phase model is that it is more practical and easier to apply in a real plant.

3. The proposed model shall only take into consideration of metabolic activities of methanogenic acetoclastic and methanogenic hydrogenophilic microorganisms. The Pinto model has an additional fermentation process. There is bound to have difficulty to observe two different processes simultaneously, which are the fermentation and bioelectrochemical process in the same reactor.

3.2.1 Mass Balances for the MEC System

In this section, the mass balances involved to generate the mathematical modelling of the MEC are presented. A list of parameters taken into account of the modelling is presented in Table 3.1.

Table 3.1: Value of parameters used in the operation of MEC

Symbol	Description
$\mu_{max,m}$	The maximum growth rate of the acetoclastic methanogenic microorganism
$\mu_{max,a}$	The maximum growth rate of the anodophilic microorganism
$\mu_{max,h}$	The maximum growth rate of the hydrogenotrophic microorganism
$q_{max,a}$	The maximum reaction rate of the anodophilic microorganism
$q_{max,m}$	The maximum reaction rate of the acetoclastic methanogenic microorganism
$K_{S,a}$	The half-rate (Monod) constant of the anodophilic microorganism
$K_{S,m}$	The half-rate (Monod) constant of the acetoclastic methanogenic microorganism
K_M	Mediator half-rate constant
K_h	Half-rate constant
Y_{H_2}	The dimensionless cathode efficiency
Y_h	The yield rate for hydrogen consuming methanogenic microorganisms
m	The number of electrons transferred per mol of H_2
P	The anode compartment pressure
M_{ox}	Oxidized mediator fraction

Table 3.1: Value of parameters used in the operation of MEC, continued

Symbol	Description
M_{ox}	Oxidized mediator fraction
β	The reduction or oxidation transfer coefficient
$A_{sur,A}$	The anode surface area
i_0	The exchange current density in reference conditions
E_{CEF}	The counter-electromotive force for the MEC
E_{app}	The electrode potentials
$K_{d,a}$	The microbial decay rates of the anodophilic microorganism
$K_{d,m}$	The microbial decay rates of the acetoclastic methanogenic microorganism
$K_{d,h}$	The microbial decay rates of the hydrogenotrophic microorganism
Y_M	The oxidized mediator yield
γ	The mediator molar mass
V_r	The anodic compartment volume
S_0	The initial conditions of organic substrate concentration in the influent and in the anodic compartment
x_{h0}	The initial conditions of hydrogenotrophic methanogenic microorganisms
x_{a0}	The initial conditions of anodophilic microorganisms
x_{m0}	The initial conditions of acetoclastic methanogenic microorganisms

The dynamic mass balance equations for components S (concentration of substrate), x_a (concentration of anodophilic microorganism), x_m (concentration of acetoclastic microorganism), x_h (concentration of hydrogenotrophic microorganism) and M_{ox} (oxidized mediator fraction per electricigenic microorganism) in the designed MEC system can be represented as follows:

$$\frac{dS}{dt} = -q_{max,a}\frac{S}{K_{S,a}+S}\frac{M_{ox}}{K_M+M_{ox}}x_a - q_{max,m}\frac{S}{K_{S,m}+S} \tag{3.1}$$

$$\frac{dx_a}{dt} = \mu_{max,a}\frac{S}{K_{A,a}+S}\frac{M_{ox}}{K_M+M_{ox}}x_a - K_{d,a}x_a - \alpha_1 x_a \tag{3.2}$$

$$\frac{dx_m}{dt} = \mu_{max,m}\frac{S}{K_{A,m}+S} - K_{d,m}x_m - \alpha_1 x_m \tag{3.3}$$

$$\frac{dx_h}{dt} = \mu_{max,h}\frac{H_2}{K_h + H_2} - K_{d,h}x_h - \alpha_2 x_h \tag{3.4}$$

$$\frac{dM_{ox}}{dt} = \frac{\gamma}{V_r x_a}\frac{I_{MEC}}{mF} - Y_M q_{max,a}\frac{S}{K_{A,a} + S}\frac{M_{ox}}{K_M + M_{ox}} \tag{3.5}$$

$$Q_{H_2} = Y_{H_2}\left(\frac{I_{MEC}}{mF}\frac{RT}{P}\right) - Y_h \mu_h x_h V_r \tag{3.6}$$

Where,

$Q_{H_2} = hydrogen\ production\ rate\ (\frac{mL}{day})$

3.2.2 Electrochemical Process

To determine the corresponding MEC voltage, theoretical values of the electrode potentials have to be subtracted by the ohmic, activation and concentration losses.

In the operation of MEC, resistance of the flow of ions in the electrolyte and electrode could result in ohmic losses. The partial resistances consist of the counter-electromotive force (E_{CEF}), activation loss (η_{act}), concentration loss (η_{conc}) and ohmic loss (η_{ohm}). Each of the partial resistances shall be determined individually. The electrochemical balance can then be written as below:

$$-E_{app} = E_{CEF} - \eta_{act} - \eta_{conc} - \eta_{ohm} \tag{3.7}$$

Ohm's Law can be applied to determine the ohmic losses ($\eta_{ohm} = I_{MEC}R_{int}$). To determine the concentration losses, it has to be divided between the anode ($\eta_{conc,A}$) and cathode ($\eta_{conc,C}$) reactant mass transfer in the MEC. Due to the small size of H_2 molecules, the concentration loss at cathode could be neglected as it results in a large diffusion coefficient of H_2 in a gas diffusion electrode used as cathode. Thus, the concentration loss could be computed using the Nernst Equation as follow (Pinto *et al.*, 2010):

$$\eta_{conc,A} = \frac{RT}{mF}\ln\left(\frac{M_{Total}}{M_{red}}\right) \quad (3.8)$$

In determining the activation losses value, the anode ($\eta_{act,A}$) and cathode ($\eta_{act,C}$) value could be separated due to slow reaction kinetics. The fact that MEC operates at high overpotential at the cathodic side (Logan *et al.*, 2008), $\eta_{act,A}$ is assumed to be significantly smaller than the $\eta_{act,C}$ and it shall be neglected. With the assumption that oxidation and reduction coefficients, which represent the activation barrier symmetry are identical, the Butler-Volmer equation could be simplified to as follows (Noren *et al.*, 2005):

$$\eta_{act,C} = \frac{RT}{\beta mF} sinh^{-1}\left(\frac{I_{MEC}}{A_{sur,A} i_0}\right) \quad (3.9)$$

Where,

$i_0 = exchange\ current\ density\ in\ reference\ conditions\ (Acm^{-1})$
$A_{sur,A} = anode\ surface\ area\ (m^2)$
$\beta = reduction\ or\ oxidation\ transfer\ coefficient$

Based on the previously defined Ohm's Law and combining equations (3.7 - 3.9), I_{MEC} can be computed as below:

$$I_{MEC} = \frac{E_{CEF} + E_{applied} - \frac{RT}{mF}\ln\left(\frac{M_{Total}}{M_{red}}\right) - \eta_{act,C}}{R_{int}} \quad (3.10)$$

As there is a presence of activation losses at the cathode, the calculation of I_{MEC} requires a numerical solution due to the nonlinear nature of equation 3.10 as $\eta_{act,C} = f(I_{MEC})$. However, there is a possibility that equation could result in the negative value of I_{MEC} in the events where the summation of $\eta_{act,C}$, $\eta_{conc,A}$ and E_{CEF} to be greater than the E_{app} in equation 3.7. As a countermeasure to such problem, only non-negative values of I_{MEC} are to be taken into consideration.

To ensure the model accuracy during the start-up period, Pinto *et al.* (2010) has proposed improvement to be implemented where R_{int} shall be linked to the concentration of electricigenic microorganisms (x_e):

$$R_{int} = R_{min} + (R_{max} - R_{min})e^{-K_R x_e} \quad (3.11)$$

Where,

$R_{min} = lowest\ observed\ internal\ resistance\ (\Omega)$
$R_{max} = highest\ observed\ internal\ resistance\ (at\ startup)(\Omega)$
$K_R = constant\ to\ determine\ the\ curve\ steepness\ (L\ mg\ x^{-1})$

Table 3.2 shows the parameters and their corresponding values used in the operation of MEC within the Simulink environment.

Table 3.2: Value of parameters used in the operation of MEC

Symbol	Value
$\mu_{max,m}$	$0.3\ d^{-1}$
$\mu_{max,a}$	$1.97\ d^{-1}$
$\mu_{max,h}$	$0.5\ d^{-1}$
$q_{max,a}$	$13.14\ mg - A\ mg - x^{-1}d^{-1}$
$q_{max,m}$	$14.12\ mg - A\ mg - x^{-1}d^{-1}$
$K_{S,a}$	$20\ mg - AL^{-1}\ or\ mg - ML^{-1}$
$K_{S,m}$	$80\ mg - AL^{-1}\ or\ mg - ML^{-1}$
K_M	$0.01\ mg - ML^{-1}$
K_h	$0.001\ mgL^{-1}$
Y_{H_2}	$0.9\ (dimensionless)$
Y_h	$0.05\ mL - H_2mg - x^{-1}d^{-1}$
m	$2\ mol - e^{-1}mol - H_2^{-1}$
P	$1\ atm$
M_{ox}	$50\ mg - Mmgx^{-1}$
β	$0.5\ (dimensionless)$
$A_{sur,A}$	$0.01\ m^2$
i_0	$0.005\ Acm^{-1}$
E_{CEF}	$-0.35\ V$
E_{app}	$10.0\ V$

Table 3.2: Value of parameters used in the operation of MEC, continued

Symbol	Value
$K_{d,a}$	$0.04\ d^{-1}$
$K_{d,m}$	$0.01\ d^{-1}$
$K_{d,h}$	$0.01\ d^{-1}$
Y_M	$34.85\ mg - M\ mg - A^{-1}$
γ	$663400\ mg - M\ mol_{med}^{-1}$
V_r	$10\ L$
S_0	$1500\ mgL^{-1}$
x_{h0}	$10\ mgL^{-1}$
x_{a0}	$275\ mgL^{-1}$
x_{m0}	$25\ mgL^{-1}$

A diagram of multiple blocks in Figure 3.4 provides established blocks of the mathematical modelling depicting the biohydrogen production via MEC. The blocks highlighted in green are the representation for the dynamic mass balance equations for components S, x_a , x_m, x_h and M_{ox}. The blocks highlighted in blue on the other hand evaluate the hydrogen production rate by the MEC system.

Figure 3.5 shows the block diagram to evaluate the current generated by the MEC(I_{MEC}). Various parameters such as $\eta_{conc,A}$, $\eta_{act,C}$, R_{int}, E_{CEF} and $E_{applied}$ are required for the computation of I_{MEC} as shown in the yellow block.

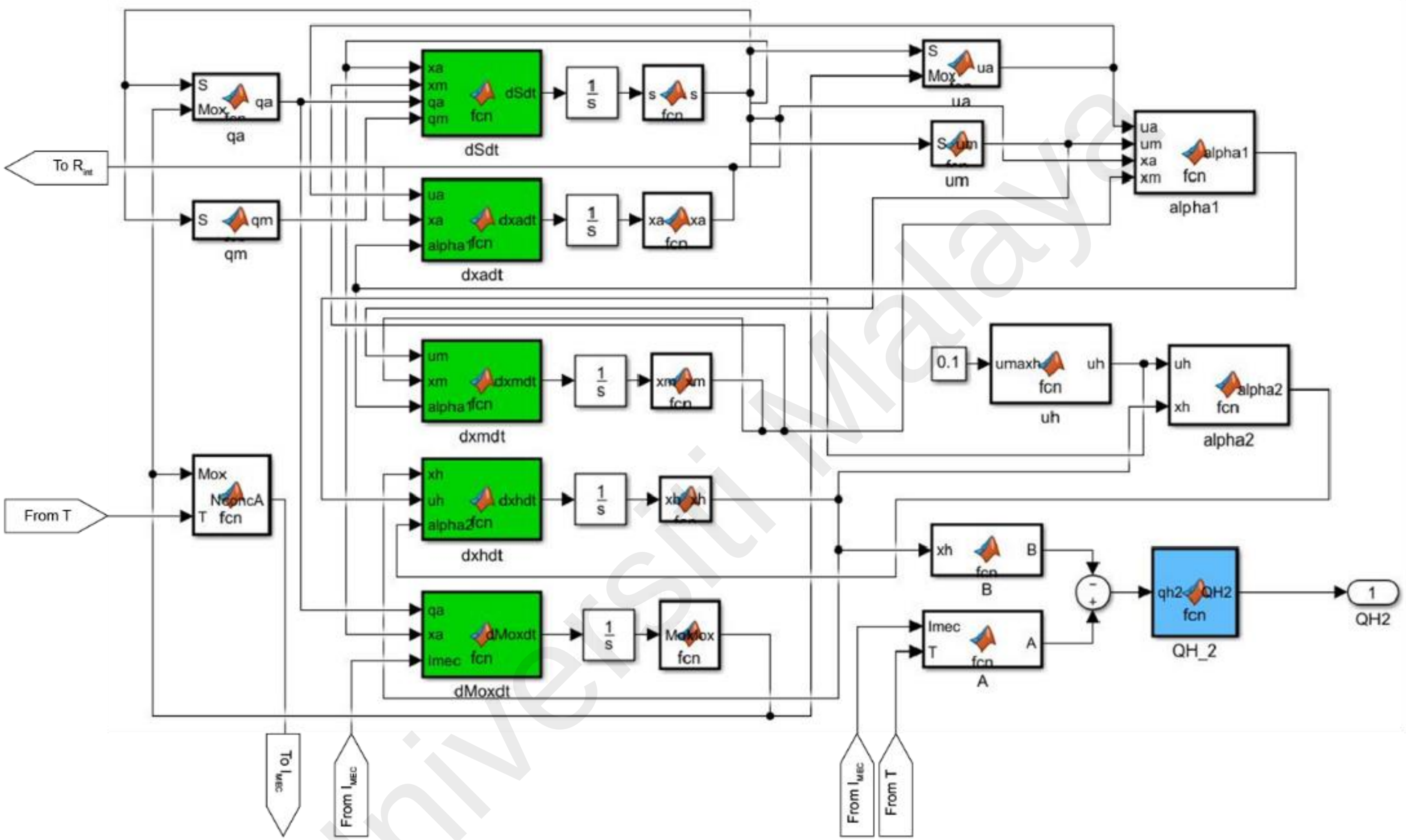


Figure 3.4: Block diagram of MEC system in the Simulink environment as represented by green blocks and biohydrogen production as represented by blue block. Detailed information of individual blocks can be referred to Appendix A

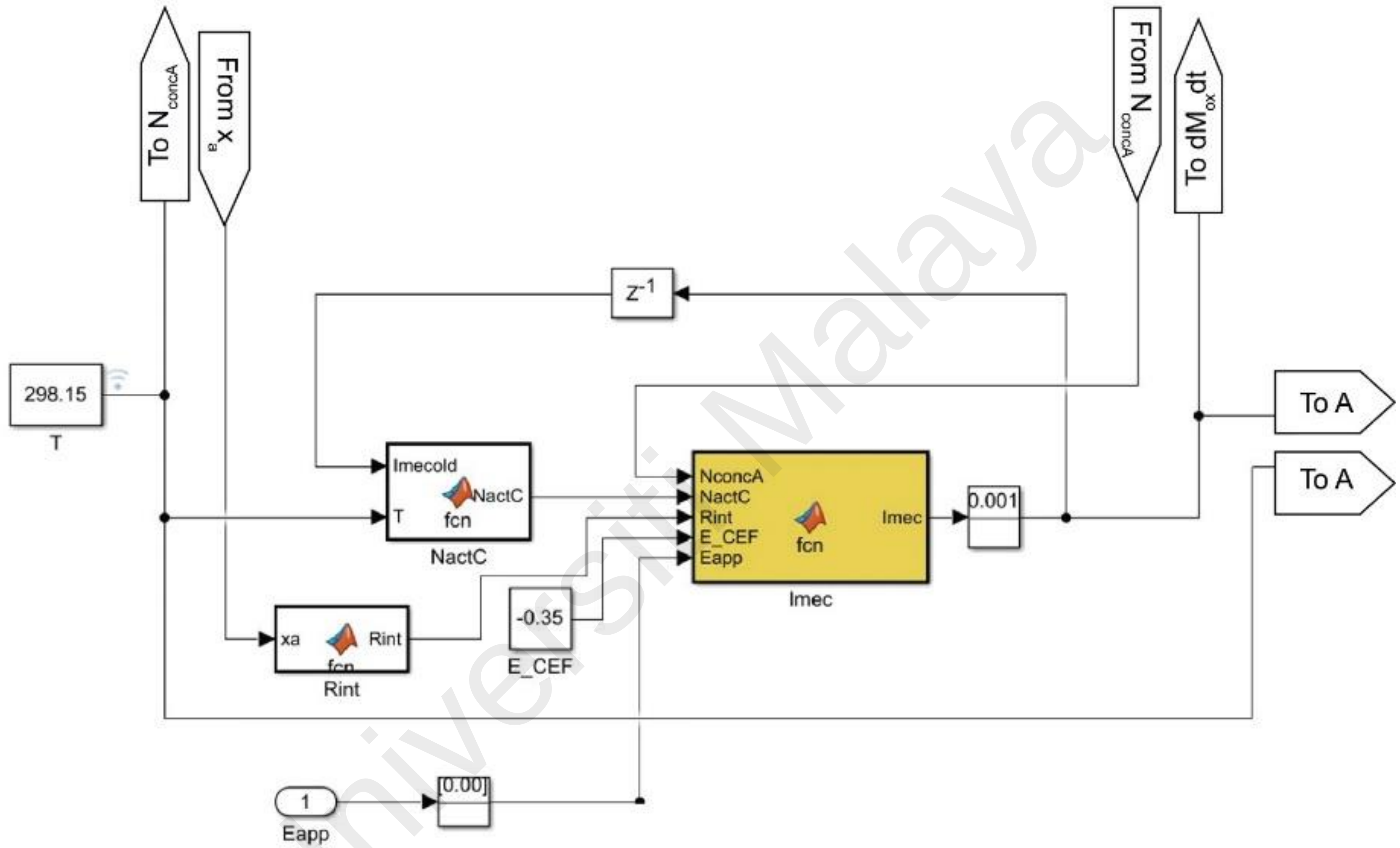
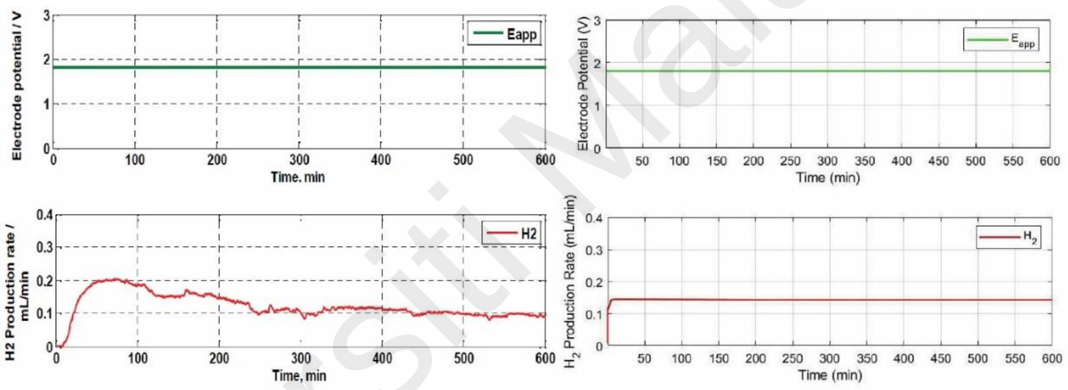


Figure 3.5: Block diagram of current generated by MEC (I_{MEC}) in the Simulink environment as represented by yellow block. Detailed information of individual blocks can be referred to Appendix A

3.2.3 Model validation for MEC via open-loop studies

In order to validate the accuracy of the MEC mathematical model adopted earlier, it is compared against experimental work, which is an open-loop experimental study of a fed-batch MEC reactor by Azwar (2017). Figure 3.6 presents the resulting hydrogen production rate at the applied constant voltage of 1.8 V. The hydrogen obtained from this work, which is depicted by Figure 3.6(b) is shown to achieve stable states with close resemblance values to that of the experimental studies as shown in Figure 3.6(a). This then validates the accuracy of the mathematical modelling adopted for this work, which is utilized in the control studies later.



(a) (b)

Figure 3.6: Model validation of MEC between (a) Azwar-modified Pinto MEC model (Azwar, 2017) and (b) this work

3.3 Design of Control Systems

The design of FLC to be implemented on the MEC system is elaborated in this section. Elaboration includes the membership functions and rules within the FLC.

Johnson *et al.* (2011) conducted a test to determine the optimal condition for hydrogen gas charging into a storage system of nine DOT 3A cylinder tanks. The refuelling of 2 hydrogen storage systems operates at a flowrate of 0.43 kg/h with pressure of 40 MPa. The refuelling process is assumed to operate at nominal room temperature of 21 °C. Further assumptions are made to cater the storage system into the MEC system by having only a single cylinder tank with down-scaling of tank by a factor of 10. As the density of gas is a function of the temperature and pressure that the gas is in (El-Banbi *et al.*, 2018), the calculations to determine the setpoint are as follow:

Determination of hydrogen gas density at pressure of 40 MPa and temperature of 21 °C

Table 3.3: Hydrogen Density at different temperatures and pressures (Hydrogen Tools).

Temperature	Pressure	
	30 MPa	50 MPa
0 °C	22.151 kg/m^3	32.968 kg/m^3
25 °C	20.537 kg/m^3	30.811 kg/m^3

Density of hydrogen gas at pressure of 30 MPa and temperature of 21 °C:

$$\rho_{H_2,1} = 22.151 + \frac{20.537 - 22.151}{25 - 0}(21 - 0) = 20.795\ kg/m^3$$

Density of hydrogen gas at pressure of 50 MPa and temperature of 21 °C:

$$\rho_{H_2,2} = 32.968 + \frac{30.811 - 32.968}{25 - 0}(21 - 0) = 31.156\ kg/m^3$$

Density of hydrogen gas at pressure of 40 MPa and temperature of 21 °C:

$$\rho_{H_2,3} = 20.795 + \frac{31.156 - 20.795}{50 - 30}(40 - 30) = 25.976\ kg/m^3$$

By interpolate between the two pressures and temperature, the hydrogen gas density at pressure of 40 MPa and temperature of 21 °C is determined at 25.976 kg/m^3. A graphical representation of the interpolation can be referred to Figure 3.7.

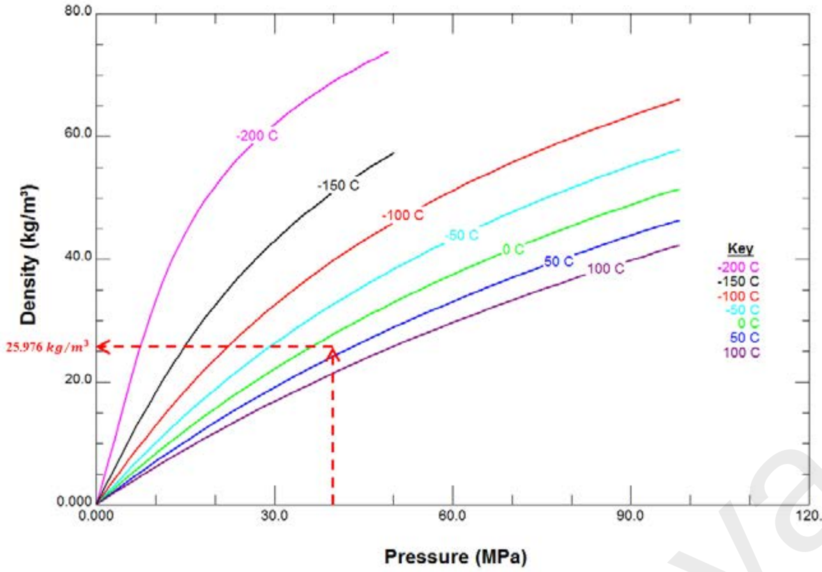


Figure 3.7: Interpolation of density of hydrogen gas at $P = 40\ MPa$ and $T = 21°C$ (Hydrogen Tools)

As the nominal flow rate of 0.43 kg/h is needed to fill up the hydrogen storage system, the daily mass flow rate of the hydrogen gas would be 10.32 kg/day. The conversion of the daily mass flow rate of hydrogen gas to volumetric flow rate based on the determined density is as follow:

$$Q_{H_2,2\ systems} = 10.32 \frac{kg}{day} \times \frac{1}{25.976} \frac{m^3}{kg} \times \frac{1000\ L}{1\ m^3} = 385\ \frac{L}{day}$$

As 385 L/day is required to fill up two systems in a day, an assumption is made that only one system filled up per day, which reduces the flowrate to 192.5 L/day. Further assumptions made are that only one out of the nine cylindrical tanks is considered for the filling up process and the single tank is scaled down to a factor of 10. This leads to our computed flow rate setpoint of 2.14 L/day.

$$Q_{H_2} = 192.5\ \frac{L}{day.system} \times \frac{1}{9} \frac{system}{tanks} \times \frac{1}{10} = 2.14\ \frac{L}{day.tank}$$

3.3.1 Fuzzy Logic Controller

Figure 3.8 represents the common scheme of implementing FLC on a closed-loop system with two inputs. Generally, the variables chosen to be the inputs are the error and derivatives of error as the objective of the FLC is to minimize the deviation of MEC output from its designated setpoint (Silva *et al.*, 2018). In this work, the first input is the error (e) at time t, which can be written as follow:

$$e(t) = Q_{H_2,Setpoint}(t) - Q_{H_2}(t) \quad (3.12)$$

The second input is the rate of change of error (de/dt) at time t. There is a single output from the FLC, which is the change of applied voltage (ΔE_{app}) at time t. The corresponding applied voltage (E_{app}) is then fed into the MEC for hydrogen production.

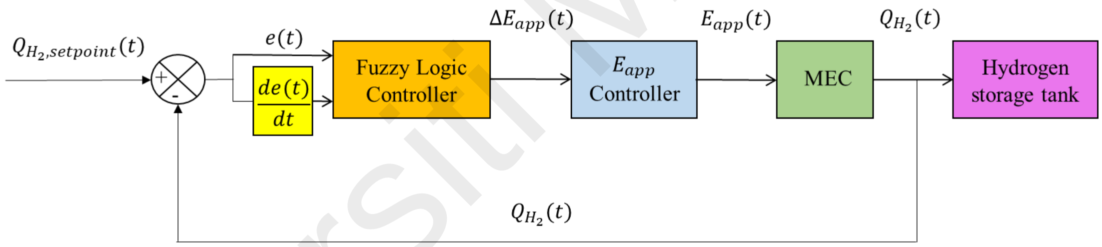


Figure 3.8: Closed-loop block diagram of MEC system with FLC

With reference to Figure 2.12, the FLC firstly converts the two inputs, which in this case are e and de/dt into suitable defined fuzzy sets by the fuzzification block. The inference mechanism then evaluates and combines membership functions with defined fuzzy rule base to determine the fuzzy output. Finally, the fuzzy output passes through the defuzzification block to be translated into a term of crisp value, which in this case is the ΔE_{app} via centroid method by determining the centre of area of fuzzy set before being fed into the MEC system.

In order to determine the values of the fuzzy sets and their respective membership functions, prior closed-loop data with implementation of control system other than the FLC is required.

In this study, triangular type membership functions with Mamdani inference is adopted. Triangular type membership functions are adopted for its simplicity upon implementation. Their excellent adaptability is known to ensure better responses when overshoot or undershoot output occurs (Jin *et al.*, 2002; Sadollah, 2018). As the development of FLC for this work requires input and output variables along with fuzzy rules that are constructed based on expert knowledge, a Mamdani fuzzy-based control approach would be appropriate.

The fuzzy domain for e is [-1.5, 1.5] with fuzzy sets of $\{N2, N1, Z, P1, P2\}$, which can be referred to Figure 3.9. Referring to Figure 3.10, the de/dt has fuzzy domain of [-280, 280] with fuzzy sets of $\{NF, NS, Z, PS, PF\}$.

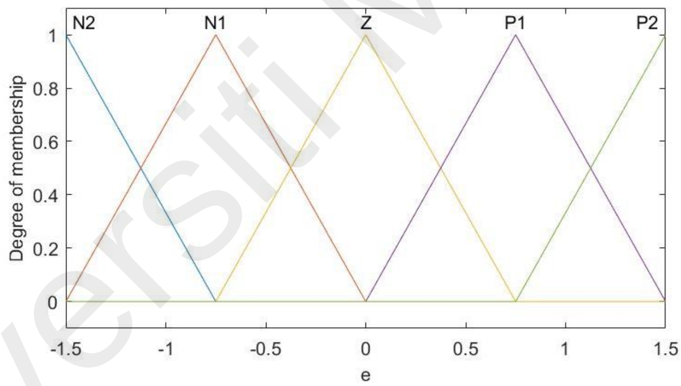


Figure 3.9: Membership function of error (e)

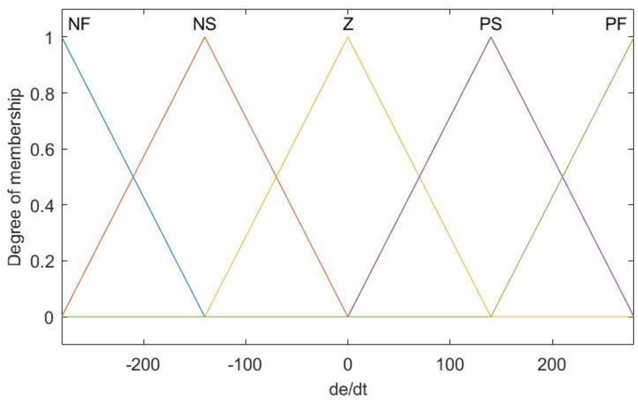


Figure 3.10: Membership function of error's rate of change (de/dt)

The output of the fuzzy control, which is ΔE_{app} manipulates the voltage applied onto the MEC system to determine the Q_{H_2}. The output also adopts the triangular type of membership functions with fuzzy domain of [-1, 1] and corresponding fuzzy sets of $\{HD, MD, LD, Z, LI, MI, HI\}$, which can be seen in Figure 3.11. Membership labels defined for the membership function of ΔE_{app} output are as follows:

$HD = High\ negative\ value\ of\ \Delta E_{app}$
$MD = Moderate\ negative\ value\ of\ \Delta E_{app}$
$LD = Low\ negative\ value\ of\ \Delta E_{app}$
$Z = Zero\ value\ of\ \Delta E_{app}$
$LI = Low\ positive\ value\ of\ \Delta E_{app}$
$MI = Moderate\ positive\ value\ of\ \Delta E_{app}$
$HI = High\ positive\ value\ of\ \Delta E_{app}$

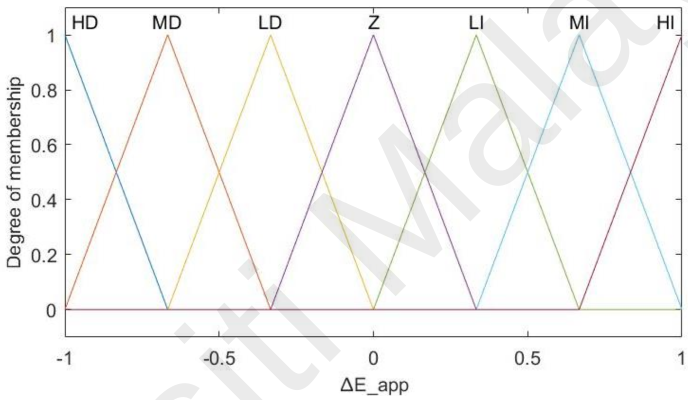


Figure 3.11: Membership function of change in applied voltage (ΔE_{app})

Table 3.4 represents the fuzzy rule base controller for the ΔE_{app} output with their corresponding e and de/dt inputs. A surface plot of the same fuzzy rule base controller to be implemented on the MEC system is illustrated in Figure 3.12.

Table 3.4: Fuzzy Rule Base controller implemented on MEC system

		Error				
		N2	**N1**	**Z**	**P1**	**P2**
de/dt	**N2**	LD	LD	MD	HD	Z
	N1	LD	MD	HD	Z	HI
	Z	MD	HD	Z	HI	MI
	P1	HD	Z	HI	MI	LI
	P2	Z	HI	MI	LI	LI

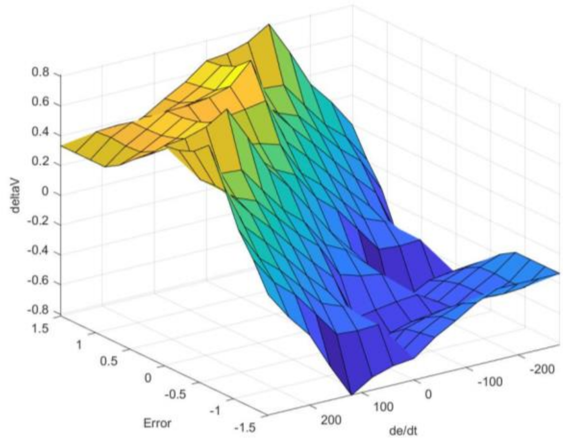


Figure 3.12: Surface plot of Fuzzy Rule Base controller to be implemented on MEC system

3.3.2 Proportional-Integral and Proportional-Integral-Derivative Controllers

To further evaluate the performance of FLC, both PI and PID controllers are implemented as well onto the same MEC system for comparison purposes. The configuration of PI and PID controllers on a MEC system can be referred to Figure 3.13. Both PI and PID controllers are tuned based on the PID Tuner application in Simulink. The application estimates the optimal tuning parameters via iteration of defined input and output of the MEC system.

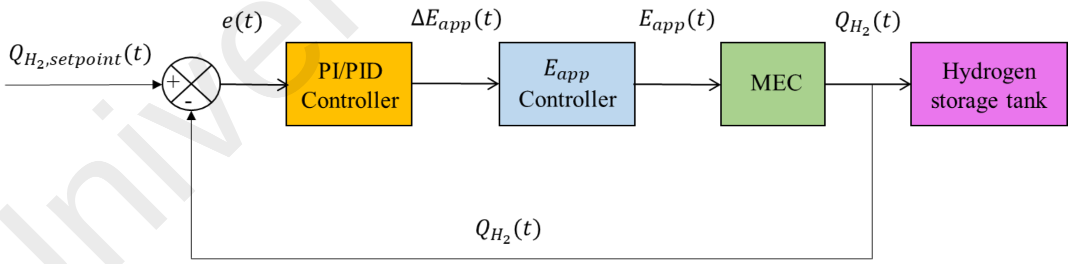


Figure 3.13: Closed-loop block diagram of MEC system with PI/PID control

The PID Tuner application in MATLAB provides a PID with 1 degree of freedom approach with tuning of PI controller has the compensator formula of:

$$P + I\frac{1}{s} \tag{3.13}$$

The PID controller has the compensator formula of:

$$P + I\frac{1}{s} + D\frac{N}{1 + N\frac{1}{s}} \quad (3.14)$$

The values for each parameter along with its respective definitions are tabulated in Table 3.5 as shown below:

Table 3.5: Tuning values for PI and PID controllers

Tuning Parameters	PI controller	PID controller
P (Proportional coefficient)	0.601	0.771
I (Integral coefficient)	0.495	0.407
D (Derivative coefficient)	N/A	-0.106
N (Filter coefficient)	N/A	0.998

3.4 Robustness Test

The FLC is tested progressively through five control schemes to evaluate its performance upon implementation onto the MEC. Subsequently, the performance of FLC is compared against the corresponding outcomes of PI and PID controllers upon implementation onto the same system.

The integral absolute error (IAE) is selected as the performance indicator of the control system. As the objective of a closed-loop controller is ensure the output value of the MEC to be as close to its designated setpoint, the computation of IAE to evaluate the capability of controllers is appropriate. A lower value of IAE is preferred as it indicates a lower accumulation of errors. The IAE can be expressed by the following equation:

$$IAE = \int_0^t \left| Q_{H_2,Setpoint}(t) - Q_{H_2}(t) \right| dt \quad (3.15)$$

3.4.1 Constant Setpoint

The MEC system is operated based on the pre-determined setpoint of 2.14 L/day and maintained throughout the whole operation. The system is observed on its rise time and overshoot outcomes. The controllers implemented is firstly be tested on their capabilities to maintain the hydrogen output of the MEC system at a constant setpoint. Figure 3.14 and Figure 3.15 illustrate the configuration for a constant setpoint study of a MEC system for FLC and PI/PID controllers, respectively.

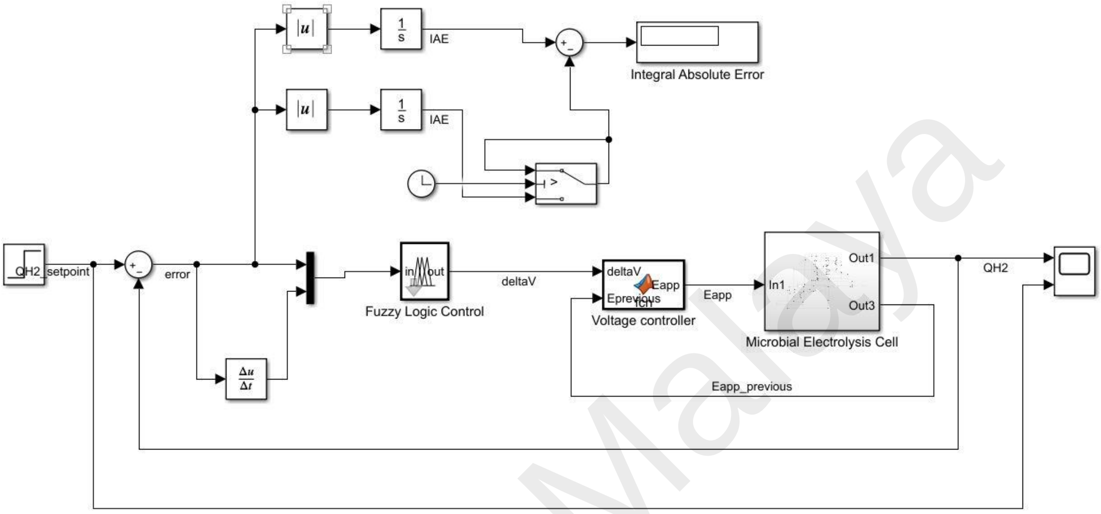


Figure 3.14: Closed-loop block diagram of MEC system with fuzzy logic controller with constant Q_{H_2} setpoint at 2.14 L/day in Simulink environment

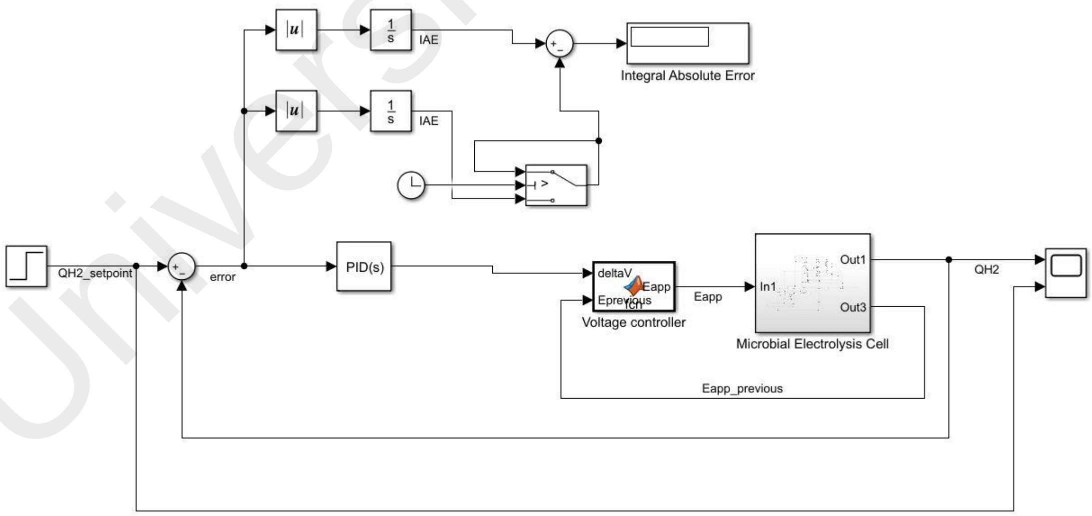


Figure 3.15: Closed-loop block diagram of MEC system with PI and PID controller with constant Q_{H_2} setpoint at 2.14 L/day in Simulink environment

3.4.2 Multiple Setpoints Tracking

Multiple setpoints values are specified in this control scheme. Response from output of the system is observed to evaluate the tracking capability of the control systems at a dynamic process. An alternating setpoints of 1.93 L/day and 2.35 L/day are defined in the operation. The setpoints alternate every 2 days within the operation. Figure 3.16 shows the configuration for multiple setpoints study of MEC system for FLC and Figure 3.17 shows the corresponding PI and PID controllers' configuration.

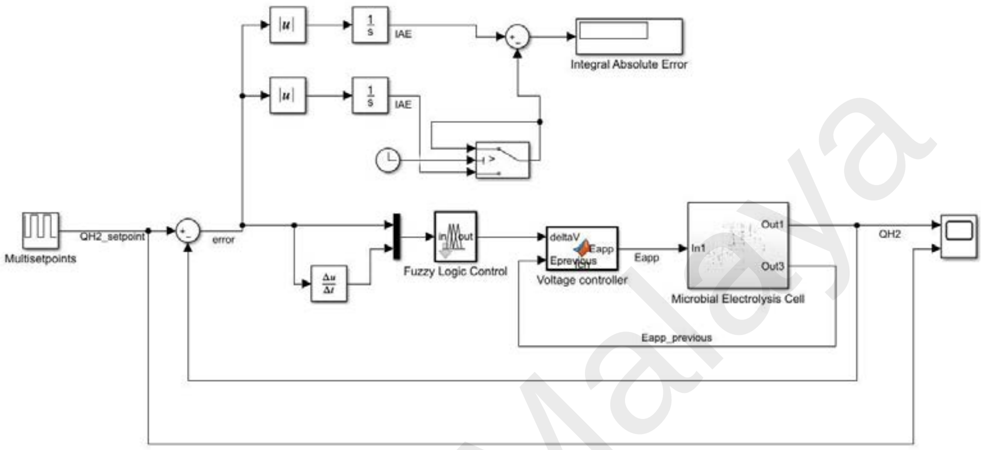


Figure 3.16: Closed-loop block diagram of MEC system with fuzzy logic controller with multiple Q_{H_2} setpoints in Simulink environment

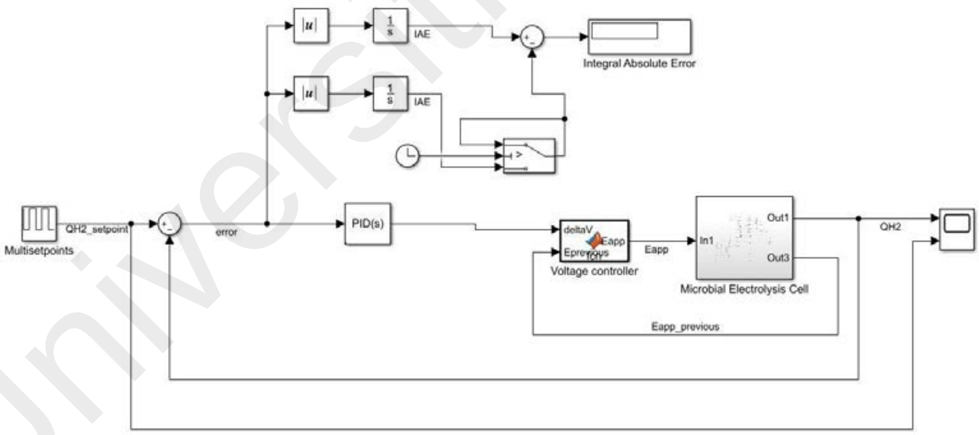


Figure 3.17: Closed-loop block diagram of MEC system with PI and PID controller with multiple Q_{H_2} setpoints in Simulink environment

3.4.3 Internal Disturbance Rejection

In the presence of internal disturbance that is physically undetectable, the control system plays a vital role to ensure the output of a system remains aligned with the setpoint. The counter-electromotive force (E_{CEF}) within the MEC system, representing the internal disturbance is varied in the operation by alternating between -0.385 V and -0.315 V at an interval of 2 days while the setpoint is kept constant at 2.14 L/day. The performance of the controllers has been evaluated on their respective performances to mitigate deviations from the setpoint upon the introduction of internal disturbances. Figure 3.18 and Figure 3.19 illustrate the configuration for internal disturbance rejection study of MEC system for FLC and PI/PID controllers, respectively.

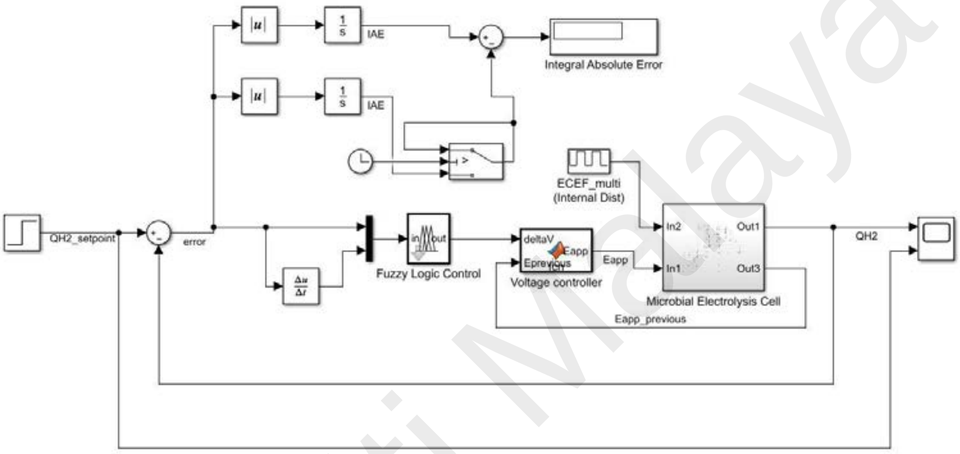


Figure 3.18: Closed-loop block diagram of MEC system with fuzzy logic controller with alternating counter-electromotive force (E_{CEF}) in Simulink environment

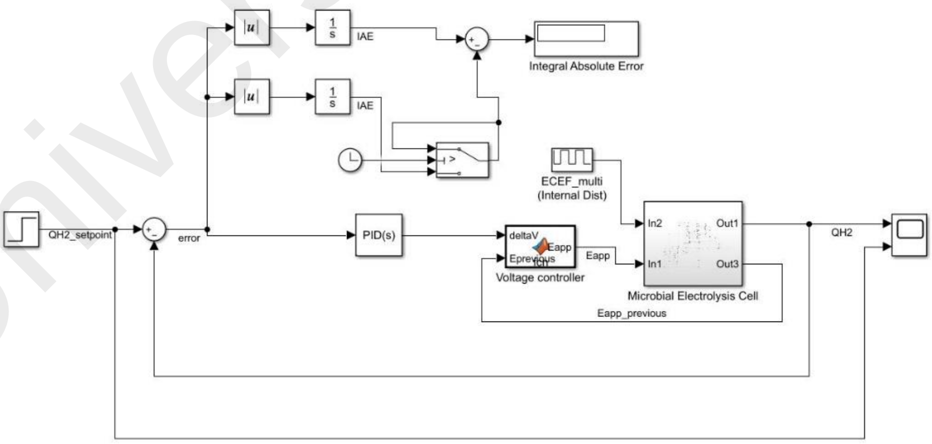


Figure 3.19: Closed-loop block diagram of MEC system with PI and PID controller with alternating counter-electromotive force (E_{CEF}) in Simulink environment

3.4.4 External Disturbance Rejection

The controllers are then subsequently tested on their performances to ensure a controlled output of hydrogen production with the introduction of external disturbances by temperature variation. The temperature is varied alternately between 303.15 K and

293.15 K for every 2 days. The setpoint is maintained at a constant hydrogen production rate of 2.14 L/day. The configuration for external disturbance rejection study of the MEC system by the FLC and PI/PID controllers can be referred to Figure 3.20 and 3.21, respectively.

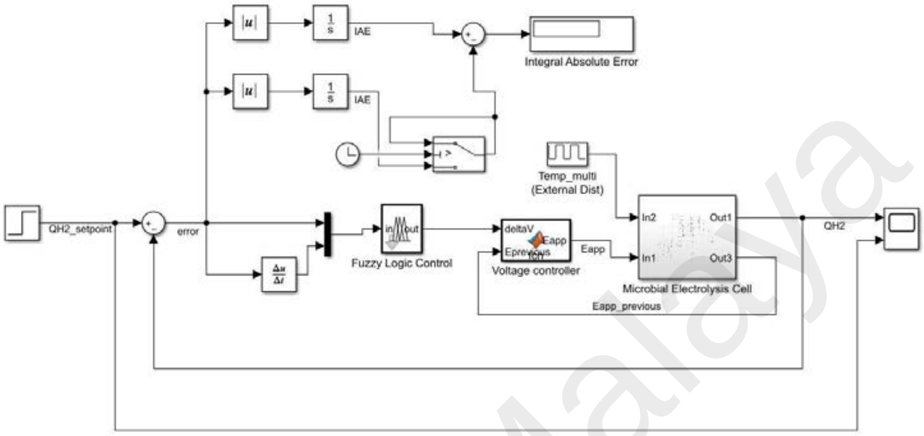


Figure 3.20: Closed-loop block diagram of MEC system with fuzzy logic controller with alternating temperatures (T) in Simulink environment

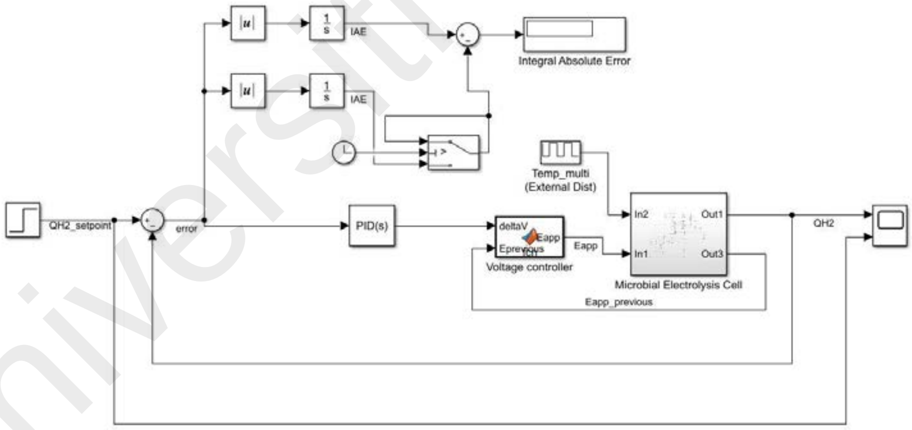


Figure 3.21: Closed-loop block diagram of MEC system with fuzzy logic controller with alternating temperatures (T) in Simulink environment

3.4.5 Noise Disturbance Rejection

To evaluate the rejection of constantly varying disturbance by FLC, noise is introduced into the system by having a band-limited white noise with noise power of 0.0001 influencing the setpoint of the system. There shall be a constant setpoint of 2.14 L/day prior to the introduction of noise throughout the whole operation. Figure 3.22 and

Figure 3.23 shows the configuration for a noise disturbance rejection study for FLC and PI/PID controllers, respectively.

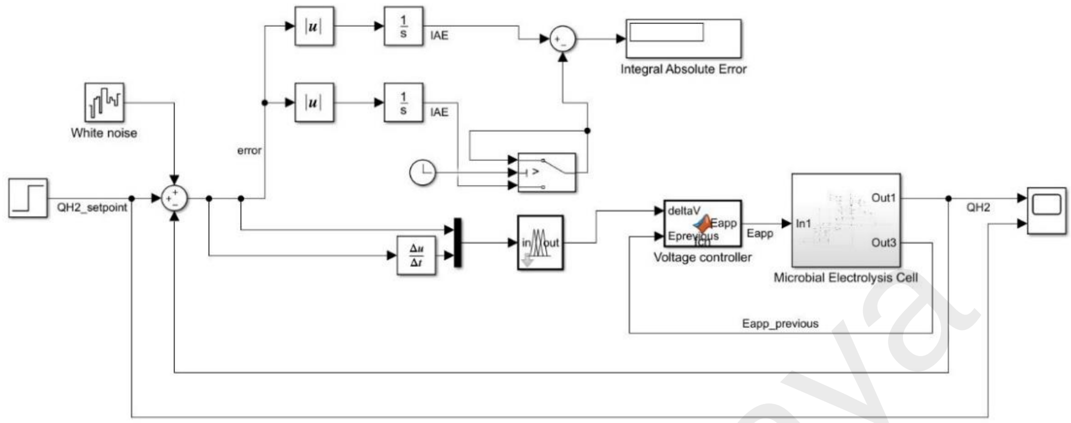


Figure 3.22: Closed-loop block diagram of MEC system with fuzzy logic controller with introduction of noise in Simulink environment

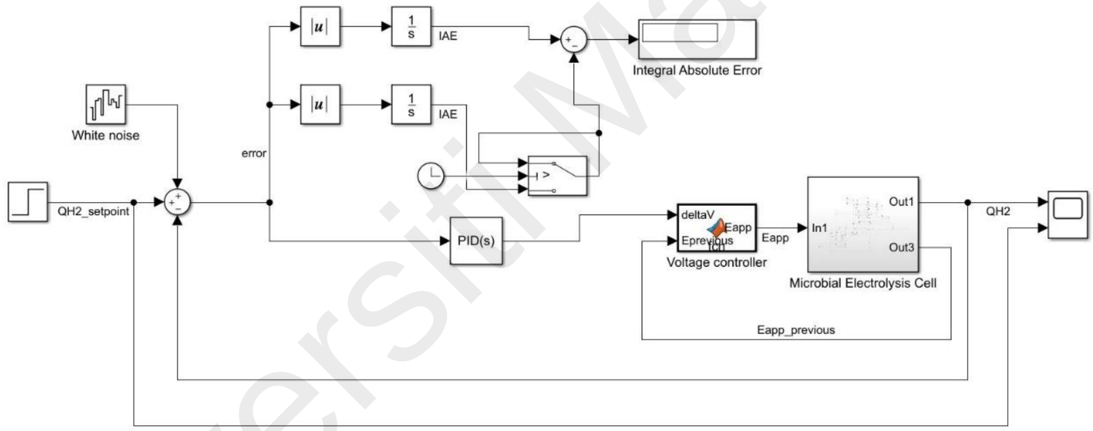


Figure 3.23: Closed-loop block diagram of MEC system with PI and PID controller with introduction of noise in Simulink environment

3.5 Summary of Chapter

The general setup of the experiment of this work is firstly designed in accordance with the research objectives. This includes MEC as the source of the hydrogen production. The produced hydrogen the MEC is then stored inside a single cylindrical storage, in which the hydrogen flow rate should be kept constant throughout the operation. The applied electrode potential onto the MEC regulates the flow rate.

A suitable mathematical modelling of the MEC system is developed to ensure accurate representation of the process within the simulation. In this study, Yahya *et al.* (2018)'s modelling work, which is modified to that of (Pinto *et al.*, 2011) is adopted. This mathematical modelling comprises of the mass balances and electrochemical process for the MEC system. The mathematically modelling is then simulated and validated against results from established open-loop experimental studies.

The fuzzy logic controller (FLC) to be implemented onto the MEC simulation is then developed based on the open-loop studies conducted earlier. The data collected from the studies provide a guideline to establish the sets of rules to be complied by the FLC. Next, the PI and PID controllers is tuned before being implemented on the MEC as well for comparison.

The controllers that are being implemented onto the MEC is subjected to 5 different control schemes to test its robustness and adaptability. These control schemes are constant setpoint, multiple setpoints tracking, internal disturbance rejection, external disturbance rejection and noise disturbance rejection.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter present the results of the microbial electrolysis cell (MEC) operation. Upon the integration of controllers onto MEC, the corresponding responses on how the biohydrogen production system adapts to various schemes such as introduction of disturbances are generated in the simulation platform.

Results comprise of graphical data depicts how fuzzy logic controller (FLC) ensures the hydrogen flow rate from MEC remains aligned with the designated setpoint. As means to gauge the performance of FLC, results from the adoption of Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers onto the MEC system are illustrated together with the FLC to provide direct performance comparisons. Concise analyses on the efficacy between the controllers are conducted, focusing on degree of overshooting and undershooting observed during hydrogen production reaching the assigned setpoints. Evaluations also include time taken for respective controllers to ensure output of MEC reaches the targeted value. Furthermore, the accumulation of error during the operation of MEC is computed via integral absolute error (IAE). The approach of assessment is to determine how well can each controller ensures the flow rate of hydrogen produced remains regulated to be as close to the setpoints. Subsequently, assessments on how timely, respective controllers ensure the readiness of hydrogen storage system is discussed. Finally, tabulated numerical data is presented to provide an indication on how well each control system performs via IAE.

4.2 Results

The outcomes of the MEC simulation with distinctive control scheme are presented in this section. Critical analyses of the results are discussed as well on how the controllers respond to various operating conditions of MEC.

4.2.1 Constant Setpoint

Based on Figure 4.1, MEC with FLC managed to reach the setpoint of the Q_{H_2} without significant overshoot being identified. Upon reaching the setpoint, the fuzzy logic controlled MEC shows no signs of deviating from the desired value.

PI and PID however exhibit overshoot in the output before settling down to the setpoint at approximately Day 4.

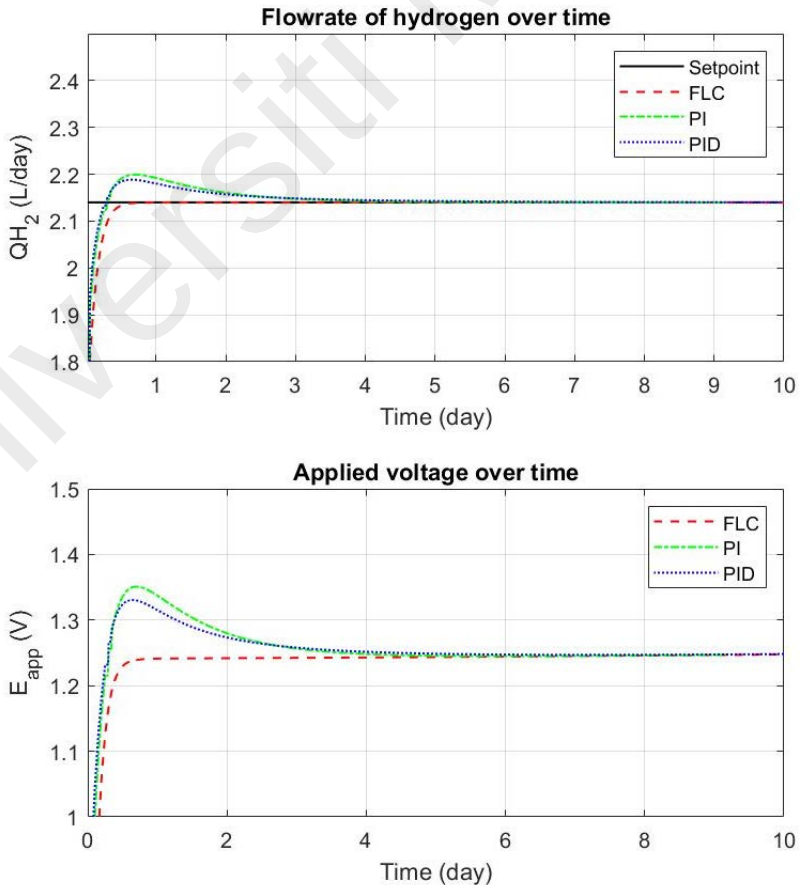


Figure 4.1: Results of closed-loop MEC response with constant Q_{H_2} setpoint at 2.14 L/day by using fuzzy logic, PI and PID controllers

4.2.2 Multiple Setpoints Tracking

Referring to Figure 4.2, FLC exhibits excellent tracking capability in the events of sudden change in setpoints. The Q_{H_2} of the fuzzy logic controlled MEC is able to reach its initial setpoint of 1.93 L/day without any significant overshoot. Upon changing of setpoint in Day 2 within the operation, the MEC system detects the change and the E_{app} increases to elevate Q_{H_2} to the latest setpoint of 2.35 L/day. Further shifting in the setpoint, produce the similar nature of output with very minimal overshoot and deviation from the setpoint.

On the contrary, the output of Q_{H_2} by the MEC system with the implementation of PI and PID controllers with noticeable overshoots and undershoots upon reaching its respective setpoints. Both PI and PID controller could not ensure the Q_{H_2} to be maintained constant for a significant period before the setpoint change due to their relatively longer settling time.

The excellent tracking capability shown in the fuzzy-based controller would be crucial in the event of sudden change in production demand. The transient time at the shift in setpoint on a MEC with FLC is shorter as compared to MEC with PI and PID controllers, which can be referred to in Figure 4.2.

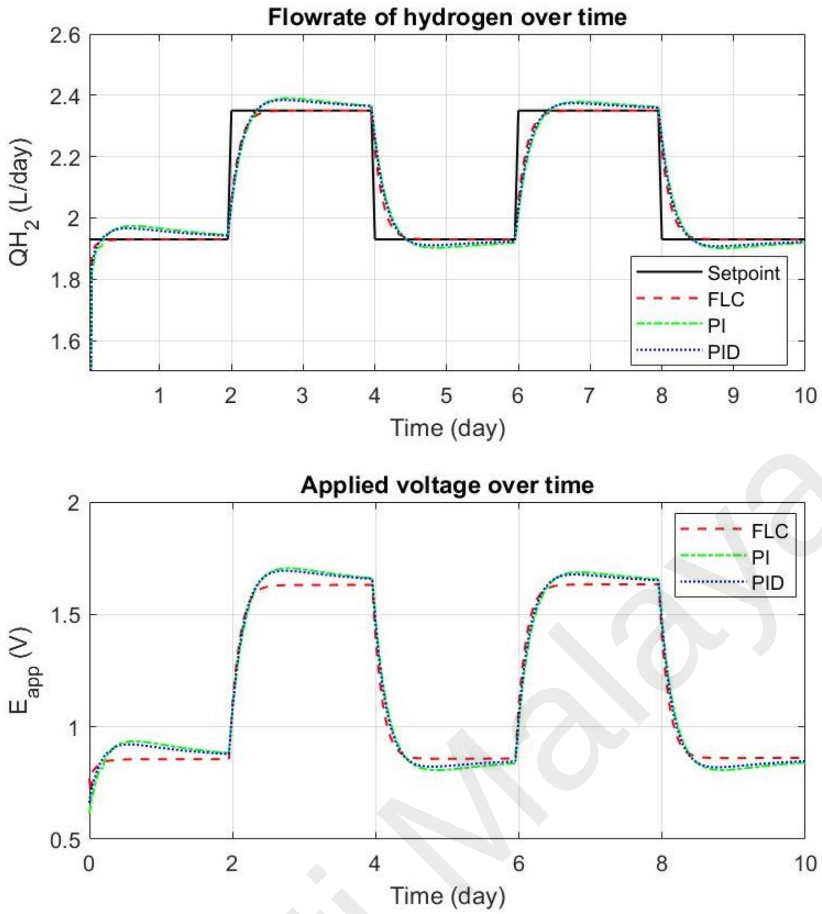


Figure 4.2: Results of closed-loop MEC response with multiple Q_{H_2} setpoints by using fuzzy logic, PI and PID controllers

Table 4.1 shows how well is the deliverable of hydrogen storage tank in the event of alternating storage demand for every 2 days. The expected daily storage capacity of the tanks varies between 1.93 L and 2.35 L. The initial storing stage at Day 1 shows a relatively large deviation from the maximum capacity of the tank by generally all 3 controllers. This is mainly due to MEC being in the phase to achieve an equilibrium state. FLC is then seen to achieve the designated storage capacity which can be observed in Day 2, 4, 6, 8 and 10 of the storing process.

The storage system filling by PI and PID controllers could not reach their respective desired volumes. This is evident by the non-zero deviation percentage from the filling capacity of the storage system. In a continuous filling system of hydrogen gas, under-filling of storage system could lead in delay in ensuring the readiness of the gas supply. Over-filling on the other hand results in wastage of hydrogen gas produced from MEC.

This better response demonstrated by FLC is contributed by precise control mechanism, enabling the flow rate of produced hydrogen gas via MEC to stabilise at a relatively shorter period. Subsequent changes in storage capacity demonstrates the FLC's capability to track new setpoints faster than PI and PID controllers.

Table 4.1: Storage tank filling for biohydrogen gas via MEC under multiple Q_{H_2} setpoints by using fuzzy logic, PI and PID controllers

Type of controller	FLC		PI		PID	
Time (day)	Volume of storage filled (L)	Deviation from setpoint of 1.93 L/ 2.35 L (%)	Volume of storage filled (L)	Deviation from setpoint of 1.93 L/ 2.35 L (%)	Volume of storage filled (L)	Deviation from setpoint of 1.93 L/ 2.35 L (%)
1	1.87	-3.06	1.89	-2.00	1.89	-1.98
2	1.93	0.00	1.95	1.25	1.95	0.97
3	2.31	-2.24	2.32	-1.37	2.32	-1.34
4	2.35	0.00	2.38	1.32	2.37	1.12
5	1.97	2.24	1.98	2.35	1.97	2.30
6	1.93	0.00	1.91	-0.96	1.92	-0.60
7	2.31	-2.24	2.31	-2.22	2.31	-2.01
8	2.35	0.00	2.37	1.01	2.37	0.78
9	1.97	2.24	1.97	2.23	1.97	2.11
10	1.93	0.00	1.91	-1.00	1.92	-0.71

4.2.3 Internal Disturbance Rejection

Referring to Figure 4.3, the MEC system FLC demonstrates its capability to ensure the Q_{H_2} is maintained at its setpoint in the presence of alternating E_{CEF}. On the other hand, the undesirable overshoots and undershoots along with longer settling time of the MEC system responses by PI and PID controllers are very much evident.

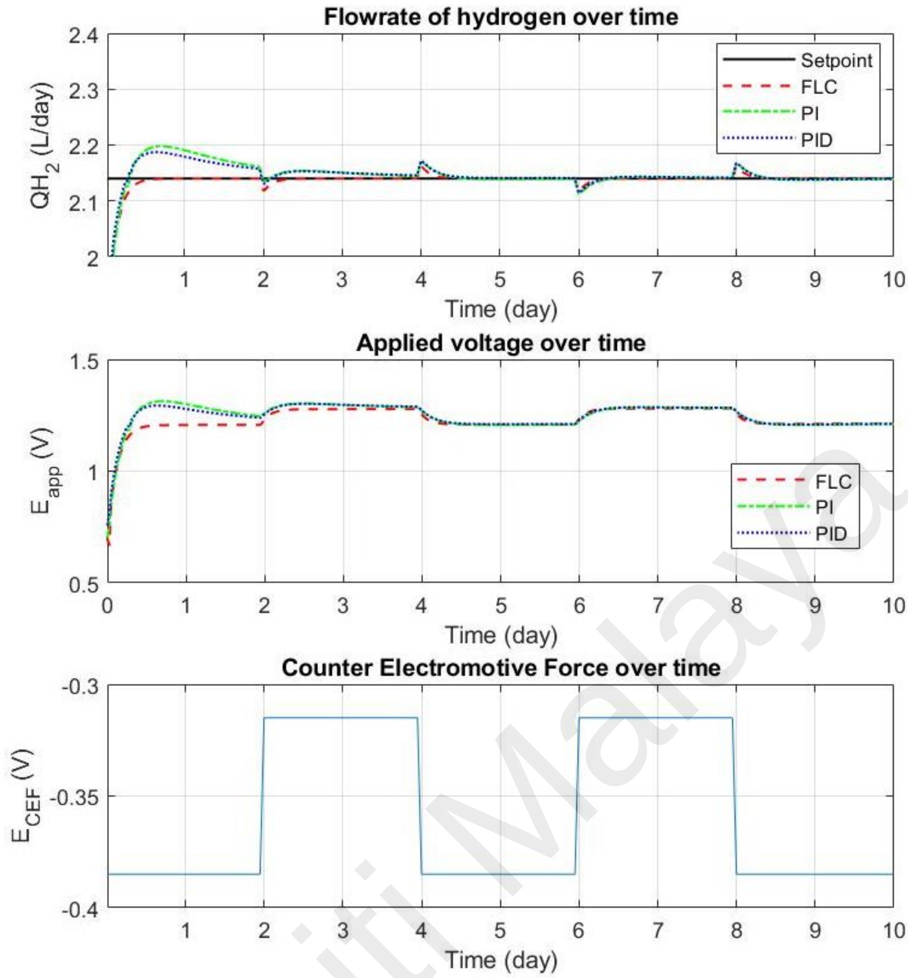


Figure 4.3: Results of closed-loop MEC response with alternating counter-electromotive force, (E_{CEF}) by using fuzzy logic, PI and PID controllers

The importance of insensitive response to internal disturbances within the hydrogen production system is crucial. In the events hydrogen flow rate overshoot, the storage system could inevitably be disrupted and consequently deviates away from the production schedule. FLC is able to ensure such stability of hydrogen production with minimal overshooting.

4.2.4 External Disturbance Rejection

Figure 4.4 depicts the severe fluctuation of Q_{H_2} away from its setpoint at the shift in operating temperature. FLC validates its superiority with a quick response to minimize error as a whole, upon the arrival of the disturbances.

PI and PID controllers do possess the capability to reject external disturbances. However, due to their distinct overshoot and longer settling time, the output of the system could never be maintained at its setpoint.

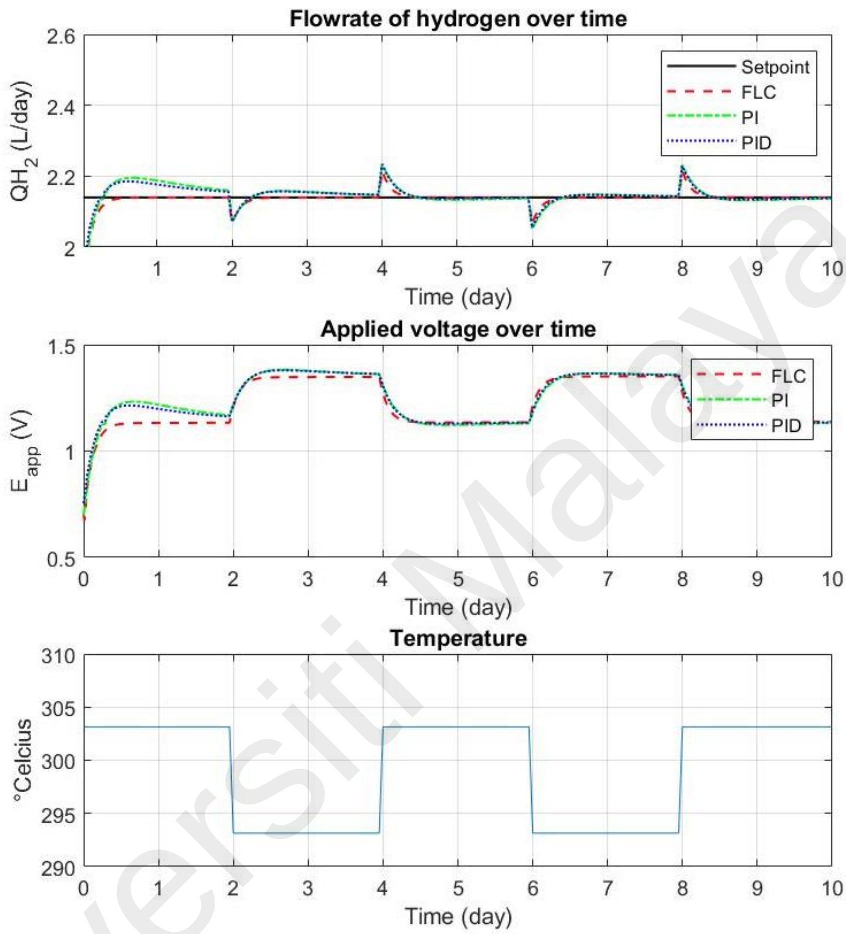


Figure 4.4: Results of closed-loop MEC response with alternating temperatures, (*T*) by using fuzzy logic, PI and PID controllers

The immediate corrective measures taken by controller in the presence of external disturbance is just as vital as in the presence of internal disturbance. This also ensures a timely readiness of the hydrogen storage system. FLC implementation on MEC has exhibit the capability to fulfil such requirement.

The timely readiness indication of the 2.14 L hydrogen storage stockpile with external disturbance being applied onto the MEC can be seen in the Table 4.2. Filling of storage system with hydrogen gas in Day 1 can be seen relatively high as all controllers as the MEC is in the phase to achieve steady state. Upon reaching a steady hydrogen production, varying the external temperature of MEC appears to have the least ramification on the fuzzy-based system. This is observed by the consistency of hydrogen filling rate on Day 2, 4, 6, 8 and 10. Despite having slight deviation from the designated hydrogen storage capacity, the performance of PI and PID controllers still lag to reject external disturbances that caused discrepancy in hydrogen flow rate.

Table 4.2: Storage tank filling for biohydrogen gas via MEC by using fuzzy logic, PI and PID controllers with alternating temperatures, (T)

Type of controller	FLC		PI		PID	
Time (day)	Volume of storage filled (L)	Deviation from setpoint of $\mathbf{2.14}\ L$(%)	Volume of storage filled (L)	Deviation from setpoint of $\mathbf{2.14}\ L$(%)	Volume of storage filled (L)	Deviation from setpoint of $\mathbf{2.14}\ L$(%)
1	2.05	-4.17	2.09	-2.39	2.09	-2.35
2	2.14	0.00	2.17	1.49	2.16	1.16
3	2.13	-0.48	2.14	0.10	2.14	0.08
4	2.14	0.00	2.15	0.50	2.15	0.50
5	2.15	0.48	2.15	0.65	2.15	0.70
6	2.14	0.00	2.14	-0.22	2.14	-0.08
7	2.13	-0.48	2.13	-0.55	2.13	-0.46
8	2.14	0.00	2.15	0.26	2.14	0.22
9	2.15	0.48	2.15	0.56	2.15	0.54
10	2.14	0.00	2.13	-0.25	2.14	-0.17

With reference to Table 4.3, a practicality indicator on the daily storage capacity of hydrogen gas produced from MEC with FLC can be seen. As stated in the earlier portion of this work, an assumption made is the storage tank has been scaled down to a factor of 10 to accommodate the hydrogen production capacity of MEC. The volumetric storage value from FLC is obtained in Table 4.2 to be resized back to the original scale. As seen in Table 4.3, the resized value appears to be in accordance with the norm of the available storage system such within the cylindrical tank capacity of 37.4 L by (Johnson *et al.*, 2011).

Table 4.3: Rescaling of hydrogen gas storage capacity via MEC by using fuzzy logic controller with alternating temperatures, (T)

Time (day)	Volume of scaled down storage (L)	Volume of storage at original scale (L)
1	2.05	20.51
2	2.14	21.40
3	2.13	21.30
4	2.14	21.40
5	2.15	21.50
6	2.14	21.40
7	2.13	21.30
8	2.14	21.40
9	2.15	21.50
10	2.14	21.40

4.2.5 Noise Disturbance Rejection

In reference to Figure 4.5, there seems to be a dynamic behaviour of Q_{H_2} and E_{app} upon the introduction of noise into the operation. It is observed that FLC is attempting to ensure the measurement of Q_{H_2} does not deviate drastically away from the designated setpoint in spite of the presence of noise.

PI and PID controllers remain having a mediocre response in comparison to the FLC with the observable poorer noise rejection capability.

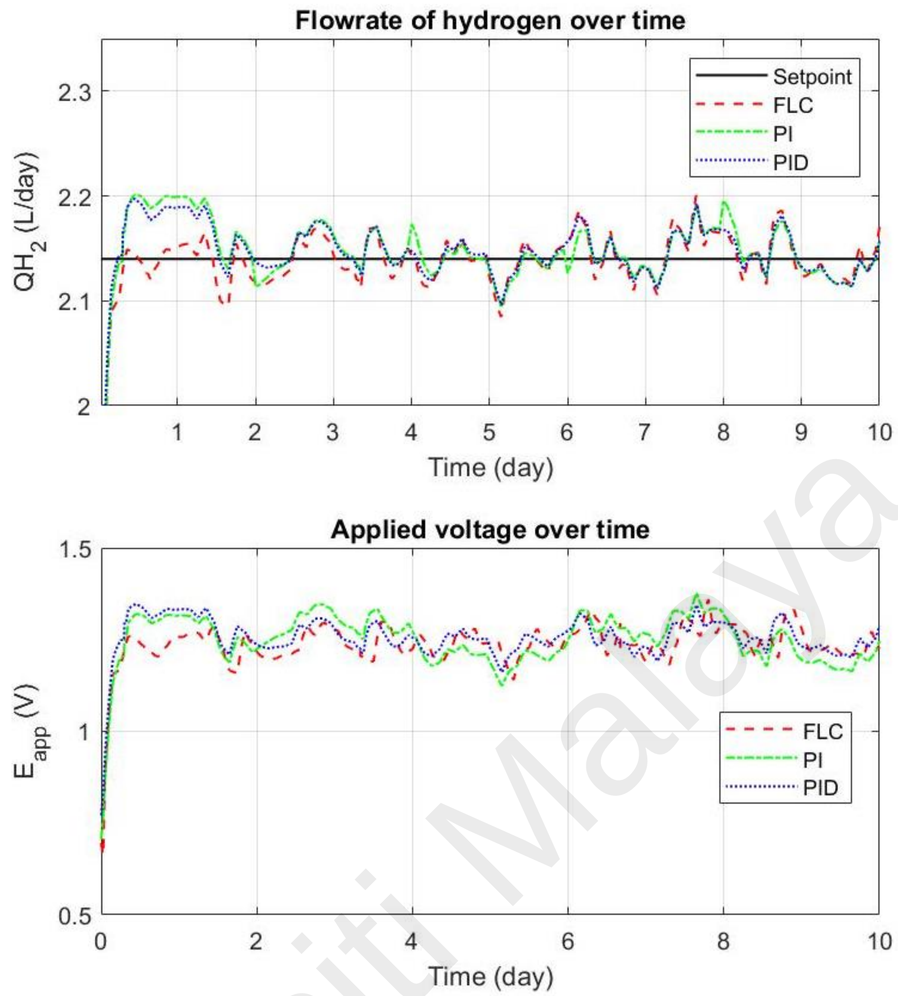


Figure 4.5: Results of closed-loop MEC response with introduction of noise by using fuzzy logic, PI and PID controllers

The implementation of FLC has generally resulted in better feedback response, which evidently in shorter settling time and smaller overshooting in comparison to the PI and PID controllers. This contributed by the configuration of the fuzzy rule base that in the earlier stage. Such rule base, which takes into consideration of membership functions of error (e) and the rate of change of error (de/dt) contributes to the FLC's robustness. This subsequently leads to a stable and consistent hydrogen flow rate from a highly dynamic MEC, ensuring a timely readiness of hydrogen storage system.

4.2.6 Integral Absolute Error

A summary of integral absolute error (IAE) for each control scheme has been tabulated in Table 4.4. As the IAE evaluates the accumulation of errors throughout the operation of MEC system, the lesser value of IAE signifies a better control system. For every control scheme that has been conducted throughout this work, FLC obtained lower value of IAE compared to the PI and PID controllers at every evaluation.

Table 4.4: Integral absolute error (IAE) for various controller schemes

Controller Scheme	IAE		
	FLC	PI	PID
Setpoint	0.0005	0.0902	0.0832
Multi-setpoint	0.1733	0.4063	0.3477
Internal disturbance	0.0130	0.1085	0.0950
External disturbance	0.0411	0.1673	0.1427
Noise disturbance	0.1459	0.2528	0.2288

Table 4.5 shows decrease in accumulated error from PID controller to the FLC, the improvement has shown to be very significant. A range of reduction between 36.2% to 99.4% in IAE is computed when FLC is being implemented onto the MEC system instead of the conventional PID controller. Significance improvement can also be observed between PI controller and FLC with reduction ranging from 42.3% to 99.4%. The evaluation indicates that FLC is generally insensitive to the presence of disturbances and has excellent tracking means to operate under changing setpoints.

Table 4.5: Percentage of reduction of integral absolute error (IAE) from PI controller to FLC and PID controller to FLC on MEC system

Controller Scheme	Decrease in IAE from PI controller to FLC	Decrease in IAE from PID controller to FLC
Setpoint	99.4%	99.4%
Multi-setpoint	57.3%	50.2%
Internal disturbance	88.0%	86.3%
External disturbance	75.4%	71.2%
Noise disturbance	42.3%	36.2%

4.3 Summary of Chapter

The corresponding results for the five control schemes are evaluated based on the respective controllers' capability to minimize overshoot and resist change due to disturbance upon implementation onto the MEC. By graphical observation, FLC produced desirable results in comparison to the PI and PID controllers as there no significant overshoot being observed and minimal deviation of designated setpoints upon the introduction disturbance into the MEC.

Numerically, FLC has accumulated the least error throughout the simulation of MEC as compared to the PI and PID controllers via IAE evaluation. The low value of IAE indicates the FLC could ensure a stable output of hydrogen production from the MEC in accordance with the setpoints that were assigned. The reduction of IAE value from PI controller to FLC ranges from 42.3% to 99.4%. While the retrofitting of FLC onto a PID controller would reduce by 36.2% to 99.4%. The steady flow rate of hydrogen gas assures the readiness of the storage system to be available on time to meet the demand of clients.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions and Summary of Work

The search for renewable alternatives to the depleting fossil fuel as energy sources remains intensive. The prospect of hydrogen energy has proven to be a viable one due to its high energy storage capacity and environmentally pleasant nature. One of the most extensively studied methods of hydrogen production is via the microbial electrolysis cell (MEC). The prime advantage of producing hydrogen through MEC is the potential substrates used in the system, which is biowaste. This thus promotes the waste to energy initiative, which reduces carbon footprint on the environment. The mathematical modelling of the MEC has been developed by various research. This work has managed to simulate the MEC for storage purposes via Simulink thus, fulfilling its first objective.

The MEC system exhibits a nonlinear dynamic to produce hydrogen gas. The presence of various microbial interactions within the system contributes to its complexity. In efforts to ensure a well-controlled condition of hydrogen production, a precise control system has to be implemented. Prior to implementing a control system onto the MEC system, a simulation of the system has been conducted. A comparison between the behaviour of the simulated MEC and an experimental MEC has been conducted for validation purposes. The Proportional-Integral-Derivative (PID) controller has been one of the pioneer and preferred selection of control system due to its simplicity of tuning. However, the nonlinear behaviour of MEC system poses a challenge to the PID controller as unforeseen disturbances affecting the system requires a retuning of the controller. The adoption of an advanced control system provides preferable results to ensure the desired output of the MEC system. In this study, an open-loop simulation has been constructed depicting the production of hydrogen gas via

MEC and stored in a repository tank. Fuzzy logic controller (FLC) is then successfully deployed onto the MEC system to control the flow rate of hydrogen produced, which complies to the fulfilment of the second objective.

The performance of FLC being implemented on MEC has been evaluated against the Proportional-Integral (PI) and PID controllers. The FLC system has been tested progressively based on various control schemes. Evaluation has been conducted through the comparison of integral absolute error (IAE), the overshoot and settling time of the outputs. MEC system with fuzzy-based controller has generally produced outputs that are much more desirable in comparison to the PI and PID controllers. This due to the FLC resulted in lower value of cumulative errors in the IAE evaluation. FLC managed to reduce the IAE values by 99.4% against PI and PID controllers, respectively. The FLC demonstrated a quicker response in the events of disturbances being present. This is contributed by the outputs' shorter settling time. The MEC systems with FLC do not display any presence of considerable overshoot in Q_{H_2} upon reaching its setpoint. The minimal overshoot in the events of setpoint changes proves FLC has excellent capability in setpoint tracking. The insensitivity to the presence of disturbances demonstrated by FLC implemented on MEC has demonstrated its efficiency to ensure a timely production of hydrogen gas. The availability and readiness of hydrogen storage system could be ensured to meet the demands of potential clients of the renewable energy. Practicality assessment has been conducted to conclude that it is feasible to storing the hydrogen gas from MEC at its original volumetric scale. The comprehensive evaluation of performance of FLC against PI and PID controller upon implementation on MEC has fulfilled the third objective of this study.

5.2 Major Contributions of this Work

As the study and understanding of MEC remain at an infancy stage, this work has provided major contributions to elevate the hydrogen production process closer to its commercialisation. This work has presented a unique methodology on how the simulation of MEC is executed. This involves the integration of the MATLAB command representing the mathematical modelling of MEC with Simulink, which provides a comprehensive graphical depiction of the process.

One of the main advantages of FLC to justify its superiority is its capability to express the amount of ambiguity in human-natured thinking in comparison to the Boolean logic. To address the issue of a highly complex MEC, FLC could aid to identify the nonlinearities of the process. The precise control demonstrated by FLC upon implementation onto MEC system could ensure a controlled flow rate of biohydrogen to be stored safely and timely inside a storage tank.

The prospect of FLC implementation could be extended beyond on similar nonlinear chemical process for maintaining stability is evident in this study.

5.3 Recommendations for Future Works

The following presents on some recommended works that could be conducted to contribute to the improvements of MEC operation. Such recommendations include:

1. To develop a more accurate and improved mathematical model to represent the MEC system. This aims to ensure a better understanding and description of the process.

2. To develop a more advanced controller such as hybrid controllers, this includes adaptive fuzzy-PID and adaptive neuro-fuzzy inference system (ANFIS). This is

to increase the precision of the controller by adapting the advantages of each individual controller.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. Gabriel Khew, M., M. A., Hussain, and A. K., Abdul Wahab, 2020. Fuzzy Logic Controller implementation on a Microbial Electrolysis Cell for Bio-hydrogen Production and Storage. *Chinese Journal of Chemical Engineering*,. (Accepted on the 1st of April 2021)