

Optimization and Control of Proton Exchange Membrane Fuel Cell Systems: A Model- Based Approach

Thesis submitted by

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2025

algorithm. *Indian Chemical Engineer*, 65(2), 125-142.

Routh, A., Ghosh, S., Dey, I., Rahaman, M., & Ghosh, A. (2024). Optimization of PEMFC pressure control using fractional PI/D controller with non-integer order: design and experimental evaluation. *Engineering Research Express*, 6(2), 025001.

Ghosh, S., **Routh, A.**, Hembrem, P., Rahaman, M., & Ghosh, A. (2024). Dynamic ant colony optimization algorithm for parameter estimation of PEM fuel cell. *Engineering Research Express*, 6(4), 323-336.

Ghosh, S., **Routh, A.**, Rahaman, M., & Ghosh, A. (2024). Multi objective optimization using artificial neural network to maximize the power output of PEMFCs. *Indian Chemical Engineer*, 66(4), 323-336.

Papers published in International Conference proceeding.

- 1.. **Routh, A.**, Ghosh, S., Rahaman, M., & Ghosh, A. (2023). DC/DC boost converter design using a fractional PI controller for a PEM fuel cell application. IICHE-CHEMCON 2023, ISBN:9789310000719
2. Ghosh, S., **Routh, A.**, Rahaman, M., & Ghosh, A. (2019). Modelling and control of a PEM fuel cell performance using Artificial Neural Networks to

maximize the real time efficiency. IEEE, 178, 1–
4.<https://doi.org/10.1109/uemgreen46813.2019.9221428>

3. **Routh, A.**, Ghosh, S., Mondal, S Rahaman, M., Ghosh, A., Harish.V. (2025). Grey Optimization of Proportional-Integral(PI) and Fractional-Order Proportional-Integral(FOPI) Parameters Using Grey Wolf Algorithm for Improved Proton-Exchange Membrane Fuel Cell Performance in DC/DC Converter. Manuscript accepted in International Conference on Smart Technology For Emerging Problem STEP(2025)

Papers Accepted in Book Chapter

Ghosh, S., **Routh, A.**, Mondal, S., Rahaman, M., Ghosh, A. (2025). Optimization of PID parameters using the Dynamic Ant Colony Algorithm in a DC/DC Converter for Performance Enhancement of PEMFCs in Springer Nature, Edited Vol. (2025)(Accepted). ISBN:978-981- 96-3840-6

Statement of Originality

I, Avijit Routh, registered on the 11th of June, 2018 do hereby declare that this thesis entitled “Optimization and Control of Proton Exchange Membrane Fuel Cell Systems: A Model-Based Approach” contains a literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis has been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the “Policy on Anti Plagiarism, Jadavpur University, 2019”, and the level of similarity as checked by iThenticate software is 4%.



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Acknowledgments

The essence of an aesthetic serenity that I am cherishing now on completion of this thesis would have surely been impossible without continuous support sourced in terms of suggestion and supervision of some genuine personalities who were always by me to make it happen. My entire endeavour would remain useless if I do not accept and admit the assistance rendered unconditionally by them. Undoubtedly, I must acknowledge the importance of their role involved directly to my efforts.

It is my pleasure to mention the name which comes first in my mind is Dr. Mehabub Rahaman attached to the Department of Chemical Engineering, Jadavpur University, Kolkata. I express my heartfelt gratitude to this man for his cooperation and guidance persistently at every stage of my work.

No appreciation is enough for Dr. Avijit Ghosh from Heritage Institute of Technology, whose consistent assistance and support helped me to reach at this point. I pay my homage for this unconditional devotion from the part of him for the sake of my work.

I must convey my regards to Dr. Saswata Bose from Department of Chemical Engineering, Jadavpur University for his continuous backing up with invaluable suggestions at every step of this research programme.

I thank to Dr. Chanchal Mondal, Head of Chemical Engineering Department, Jadavpur University, Kolkata for his production of all the facilities during the course of this journey. I could never proceed without this support.

I would like to convey my gratitude to Mr. Sankhadeep Ghosh, research scholar at Jadavpur University (Chemical Engineering Dept.), Kolkata, all the faculty members, technical and non-technical staff in the Chemical Engineering Department, Jadavpur University, Kolkata for their help whenever I needed.

I am thankful to my colleague Dr. Indranil Dey for his continuous cooperation and support during this journey. I cannot forget my friends Dr. V.S.K.V Harish, Mr. Avijit Pandit, Mr. Sunetra Mukherjee, Mr. Pintu Hembrem, Mr. Saikat Mondal, Mrs. Barsha Roy, and Mr. Tamal Santra for their support.

I would like to express my heartfelt appreciation to my beloved wife **Mrs. Harprit Routh** for her unwavering emotional support and various additional contributions that have been crucial during the process of completing this thesis. I must remember my daughter **Ishana** for her sacrifice of affection which she desired from me in order to leave me space to think over my Ph.D. My heartfelt gratitude and indebtedness are due to my mother **Smt. Swapna Routh**. I heartily acknowledge all my relatives for their love and affection towards me.

Above all, I want to convey my sincere gratitude and respect to "Eswara-supreme being," whose heavenly light and warmth gave me the fortitude, inspiration, faith, and strength to keep the pace of my research strong even during difficult times.

Date: 10/11/2025



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Abstract

The development of proton exchange membrane fuel cells, or PEMFCs, has advanced the search for sustainable and clean energy sources significantly. These fuel cells are an appealing substitute for conventional internal combustion engines because of their high theoretical efficiency, quiet operation, and almost negligible emissions, which come from the electrochemical reaction of hydrogen and oxygen. Nevertheless, there are a number of obstacles that prevent PEMFCs from achieving their optimum theoretical efficiency in real applications. These difficulties are mostly caused by the intricate flow and pressure control within the PEMFC stack, which can result in problems including flooding, catalyst deterioration, and decreased efficiency.

This thesis suggests creating and implementing sophisticated control strategies—with a particular emphasis on fractional-order controllers—to address these issues. The potential of fractional-order dynamic models to more correctly depict real-world circumstances in comparison to conventional integer-order models is becoming more widely acknowledged. This study makes use of the special qualities of fractional calculus to improve PEMFC control and optimization, which raises the devices' overall performance, stability, and efficiency.

A seventh-order nonlinear PEMFC model is introduced at the outset of the thesis and linearized to make control technique implementation easier. Accurate initial conditions and equilibrium points are taken into consideration during the linearization process, guaranteeing that the model closely resembles the dynamic behaviour of the real system. One common disruption in real-world applications, fluctuating load current, is considered a significant characteristic that impacts the system's performance. The main aim of this project is to use a

fractional PID (Proportional-Integral-Derivative) controller optimized by a genetic algorithm (GA) to create a control rule for a multi-input, multi-output (MIMO) system.

The $PI^\lambda D^\mu$ (FOPID) form of the fractional PID controller is specifically engineered to maximize the PEMFC reactor's inherent reaction. The objective is to continue producing the intended amount of power notwithstanding ambiguities and disruptions. Since of its non-integer order components (λ and μ), the FOPID controller is especially well-suited for this application since it may offer a finer level of control over the dynamic behaviour of the system. By providing more tuning options, these parts help the controller strike a more accurate balance between overshoot, reaction time, and stability.

A lot of simulations were run to confirm that the FOPID controller works as intended. The outcomes show that, especially in terms of stability and overshoot, the FOPID control approach performs noticeably better than conventional PID control. With a response time of less than 0.1 seconds, the PEMFC system's operational efficiency increased by 2%, demonstrating the controller's capability to react to system changes quickly and precisely.

The thesis tackles the crucial problem of pressure regulation at the fuel cell's cathode side in addition to maximizing the dynamic response of the PEMFC. Flooding, which can happen when too much water builds up inside the cell, can be avoided by carefully controlling the hydrogen and oxygen inflow flow rates and pressures. Flooding causes a drop in total efficiency as well as a reduction in the catalyst's performance. Thus, in order to guarantee ideal PEMFC performance, the thesis highlights how crucial it is to maintain constant exponential pressure at the cathode side.

The study investigates the development and application of a fractional PI/D controller intended primarily for pressure control. The controller is intended to accomplish three main

goals: first, it will monitor the PEMFC's operating pressure and determine which fractional PID controller is best based on which has the lowest Integration Absolute Error (IAE) to disturbances; second, it will assess the fractional PID controller's effectiveness in achieving optimal plant performance by comparing its IAE performance with that of conventional SIMC (Simplified Internal Model Control) rule based PID controller; and third, it will use MATLAB software to design a non-integer order PEMFC plant with the fractional controller and compare the results with existing models.

The thesis compares the performance of the fractional controllers with traditional optimization techniques, such as Genetic Algorithm (GA)-based PI, Particle Swarm Optimization (PSO)-based PI, and Grey Wolf Optimization (GWO)-based FOPI controllers, in order to further validate the suggested control strategies. Mathematical Simulink models of a PEMFC system with two inputs—oxygen air flow and hydrogen consumption—were used to perform these comparisons. A number of important parameters, such as rising time, maximum overshoot, and fitness function values (IAE, ISTE, and ITAE), were used to assess the controllers' performance.

These comparisons show that the fractional controllers, and especially the GWO-FOPI controller, perform better than the conventional PI controllers on every metric. Better overall stability, less overshoot, and quicker reaction times were all displayed by the GWO-FOPI controller. These results demonstrate how fractional-order control methods can be used to improve PEMFC system performance and provide a more reliable and effective solution than traditional integer-order controllers.

To sum up, this thesis offers a thorough investigation of sophisticated PEMFC control schemes, with an emphasis on fractional-order controllers. The study highlights the many

benefits of employing fractional calculus in control system design and optimization for intricate dynamic processes. PEMFC systems can benefit greatly from the higher stability, decreased overshoot, and increased efficiency of the proposed fractional $PI^\lambda D^\mu$ (FOPID) and PI/D controllers. Fractional-order control techniques have the potential to revolutionize the regulation of PEMFCs and other comparable systems, opening the door to more dependable, efficient, and sustainable energy solutions, as demonstrated by the successful deployment of these controllers in simulations.

Tables of Contents

Chapter 1: Introduction	1-24
1.1 Background and motivation.....	2
1.1.1 Introduction to PEMFC technology	2
1.1.2 Advantages of PEMFCs over traditional internal combustion engines	4
1.1.3 Challenges in maximizing PEMFC efficiency	6
1.2 Problem Statement.....	13
1.2.1 Issues related to flow and pressure management in PEMFCs.....	13
1.2.2 Difficulties with pressure regulation	14
1.3 Adaptive load reaction and membrane stress in transient condition.....	15
1.3.1 The requirement for better control methods.....	15
1.3.2 Motivation for the research	16
1.3.3 Research gap Identified	17
1.4 Research objectives.....	17
1.4.1 Using fractional-order controllers to develop and implement advanced control strategies.....	18
1.4.2 Improving PEMFC efficiency under different operating condition.....	19
1.5 Scope and significant	20
1.5.1 Overview and scope of the research.....	20
1.5.2 Importance of fractional-order control in improving PEMFC efficiency	21
1.6 Thesis structure.....	22

Chapter 2: Literature Review	25-79
2.1 Proton exchange membrane fuel cells (PEMFCs)	26
2.1.1 Working principle and operational characteristics	33
2.1.2 Key PEMFC components and their Roles.....	39
2.1.2.1 Layers of catalysts and membrane thickness	40
2.1.2.2 Gas diffusion layers (GDLs).....	42
2.1.2.3 Bipolar plates	45
2.1.2.4 Additional important elements.....	46
2.2 Challenges in PEMFC performance	47
2.2.1 Issues related to hydrogen and oxygen flow management.....	48
2.2.2 Impact of flooding and pressure variations on performance	51
2.3 Control techniques for PEMFCs operation	54
2.3.1 Overview of traditional PID control in PEMFC	54
2.3.2 Introduction to fractional-order control.....	57
2.3.3 Fractional calculus.....	58
2.3.4 Comparison of fractional-order and integer-order controllers	60
2.4 Optimization algorithms for controller design	62
2.4.1 Genetic Algorithms (GA)	64
2.4.2 Particle Swarm Optimization (PSO)	65
2.4.3 Grey Wolf Optimization (GWO).....	67
2.4.4 Comparison of different optimization techniques	70
2.5 Recent advanced trends in PEMFC control	71
2.5.1 Summary of recent research and advancements in PEMFC control	71
2.5.2 Gaps identified in current research.....	77
2.5.3 centre of focus for research	79

Chapter 3: Methodology.....	80-125
3.1 Introduction.....	81
3.1.1 Basic modelling equation related to PEMFC	83
3.1.2 Dynamic air feed model in its entirety	85
3.1.3 Algorithm to develop a fractional model to design controller	90
3.1.3.1 Integer order plant with integer order controller	95
3.1.3.2 Fractional order controller-based Integer order plant.....	96
3.1.3.3 Fractional order plant with fractional order-based controller.....	96
3.2 Mathematical model of 7th order PEMFC with problem statement	97
3.2.1 Mathematical modelling of PEMFC.....	98
3.2.2 Linearization of non-linear PEMFC	103
3.2.3 Problem formation due to dynamics of PEMFC.....	104
3.3 Modelling of proposed fractional $PI^{\lambda}D^{\mu}$ controller using genetic algorithm for controlling the PEMFC model.....	105
3.3.1 Modelling of proposed FOPID	106
3.3.2 Integrating FOPID with GA.....	107
3.4 Optimization methodology approach.....	112
3.4.1 PEM fuel cell.....	112
3.4.2 The conventional PI controlled DC/DC converter	115
3.4.3 Fractional order proportional and Integral (FOPI) controller	116
3.4.4 Particle Swarm optimization (PSO) and PSO-based FOPI (PSO-FOPI) controller	118
3.4.5 Genetic algorithm (GA) and GA-based FOPI (GA-FOPI) controller.....	120
3.5 Mathematical modelling of GWO for PEMFC	121

Chapter 4: Results and Discussion	126-155
4.1 Simulation of fractional order plant with and without FOPID	127
4.2 Simulation of GA based FOPID for PEMFC	134
4.3 Comparison with GA based PID and FOPID controller.....	142
4.4 DC/DC converter optimization using GWO.....	144
Chapter 5: Conclusions and Future Work	156-163
5.1 Summary of Findings	157
5.1.1 Key results and contributions of the research	157
5.1.2 Effectiveness of fractional-order controllers in optimizing PEMFC performance.....	158
5.2 Conclusions.....	158
5.2.1 Overall impact of the proposed control strategies	158
5.2.2 Practical implications for PEMFC operation and efficiency.....	161
5.3 Future research directions	161
5.3.1 Potential areas for further investigation	161
5.3.2 Application of fractional-order control techniques to other energy systems	162
5.4 Final remarks	162
5.4.1 Summary of the thesis and its contributions to the field	162
6. Appendix	164-165
Appendix A.....	165
7. References.....	166-180

List of Figures

Figure 2.1	Feedback-feed-forward control strategy	29
Figure 2.2	State feedback control for PEEMFC	29
Figure 2.3	A supervisory layer strategy which determines set point to lower loop.....	30
Figure 2.4	Fractional PID block diagram.....	31
Figure 2.5	GA-FOPI structure.....	32
Figure 2.6	PEM fuel cell basic diagram.....	34
Figure 2.7	Activation losses as a function of current density	37
Figure 2.8	Activation losses as a function of current density	37
Figure 2.9	PEM fuel cell polarization curve	38
Figure 2.10	PEM fuel cell power curve	38
Figure 2.11	Ohmic losses due to layer thickness	42
Figure 2.12	The polymer fuel cell plate experiences transient heat conduction at a) 10 and b) 120 seconds.....	44
Figure 2.13	Main components of PEMFC	47
Figure 2.14	Basic PID controller	57
Figure 2.15	GA based approach for PEMFC	65
Figure 2.16	PSO approach for PEMFC.....	66
Figure 2.17	GWO basic principle for PEMFC.....	69
Figure 3.1	Step response of FOPTD the system	89
Figure 3.2	Nyquist diagram of FOPTD system	89
Figure 3.3	System identification for non-integer order system.....	92
Figure 3.4	Algorithm steps for identifying a fractional order (FO) model	93
Figure 3.5	PEMFC working diagram.....	98
Figure 3.6	Equivalent circuit diagram for dynamics of PEMFC	104
Figure 3.7	FPID based controller	107

Figure 3.8 Proposed FPID integrated with GA 110

Figure 3.9 Final model integrated with GA 111

Figure 3.10 PEM Fuel cell basic structure 113

Figure 3.11 DC/DC converter basic block..... 116

Figure 3.12 FOPI block diagram for PEM fuel cell (PEMFC)..... 117

Figure 3.13 PSO-FOPI block set..... 119

Figure 3.14 GA-FOPI structure..... 121

Figure 3.15 Grey wolf optimization for FOPI 122

Figure 3.16 DC/DC boost converter design for PEM fuel cell 123

Figure 3.17 Complete flowchart of methodology 124

Figure 4.1 Supply manifold pressure comparison for different cases..... 133

Figure 4.2 Open loop response for H₂ and O₂ pressure 137

Figure 4.3 Ziegler Nichols open loop response for H₂ pressure 137

Figure 4.4 System state response with zero input 137

Figure 4.5 Closed loop response of H₂ pressure using GA based FOPID controller.... 138

Figure 4.6 Closed loop response of H₂ pressure using GA based PID controller 138

Figure 4.7 Closed loop response of O₂ pressure using GA based FOPID controller.... 139

Figure 4.8 Closed loop response of O₂ pressure using GA based PID controller..... 139

Figure 4.9 Ziegler Nichols closed loop response for H₂ pressure..... 139

Figure 4.10 Step response of H₂ with Z-N method, PID and FOPID 140

Figure 4.11 Step response of O₂ with PID and FOPID..... 141

Figure 4.12 Proposed model parameter evaluation..... 141

Figure:4.13 Fuel cell output current voltage and power transient response without
converter 146

Figure 4.14 Voltage and current across the load without adjusting the PI controller.... 146

Figure 4.15 Voltage and current across the load using GWO based dc-dc converter 148

Figure 4.16	Output voltage and current due to change of voltage in PEMFC after 1 second	148
Figure 4.17	Output voltage and current due to change of voltage in PEMFC after 5 second	149
Figure 4.18	Ripple content in DC voltage and current across the load.....	149
Figure 4.19	PEM fuel cell terminal voltage and current variation at 10 second	150
Figure 4.20	Converter terminal voltage and current using PSO-FOPI optimization in change in load	150
Figure 4.21	Converter terminal voltage and current using GA-FOPI optimization in change in load.....	150
Figure 4.22	Converter terminal voltage and current using GWO-FOPI optimization in change in load	151
Figure 4.23	Power fluctuation due to change in load	151
Figure 4.24	PEM fuel cell terminal voltage and current in change in load	152

Lists of Tables

Table 1.1	Different stages of PEMFC	3
Table 2.1	Comparison between traditional and fraction order controller	63
Table 2.2	Comparison of optimization methods	70
Table 2.3	An overview of PEMFC fuel control schemes	74
Table 3.1	Steps involve in GA	109
Table 3.2	Conventional & FOPI model values	118
Table 4.1	Simulation parameters of PEMFC system	128
Table 4.2	Controller parameter for different plant	132
Table 4.3	Transient response for different controller used for this study	132
Table 4.4	Performance metric of different controller	133
Table 4.5	Improvement percentage of performance metric in different control scheme.....	133
Table 4.6	PEMFC parameters	134
Table 4.7	Matrix value for linearizing the PEMFC	135
Table 4.8	Confusion matrix.....	141
Table 4.9	Comparison with GA based PID and FOPID controller.....	144
Table 4.10	PEMFC parameters	145
Table 4.11	Design parameter and constrain considered for optimization.....	147
Table 4.12	Conventional PI & FOPI model values.....	153
Table 4.13	Comparison with the existing models	153
Table 4.14	Performance metric comparison	153

Nomenclature

Parameter	Symbol
Atmospheric pressure	P_{atm}
Saturation pressure	P_{sat}
Average ambient air relative humidity	ϕ_{atm}
Atmospheric temperature	T_{atm}
Air-specific heat ratio	γ
Stack temperature	T_{st}
Specific heat of air	C_p
Universal gas constant	R
Molar mass of oxygen	M_{O_2}
Molar mass of nitrogen	M_{N_2}
Molar mass of vapour	M_v
Molar mass of air	$M_{a,atm}$
Faraday's constant	F
Cathode volume	$V_{cathode}$
Supply manifold volume	V_{sm}

Compressor motor mechanical efficiency	η_{cp}
Compressor efficiency	η_{cm}
Compressor and motor inertia	J_{cp}
Compressor motor resistance	R_{cm}
Motor constant	K_t
Oxygen mole fraction	$y_{o_2,atm}$
Cathode inlet orifice constant	$K_{cathode,in}$
Cathode outlet throttle discharge coefficient	C_D
Cathode outlet throttle area	A_T
Number of cells in fuel cell stack	N

CHAPTER 1

INTRODUCTION

1.1 Background and motivation

1.1.1 Introduction to PEMFC technology

Proton Exchange Membrane Fuel Cells, or PEMFCs, are a significant development in the search for efficient and clean energy sources. With the world facing more and more challenges related to the use of fossil fuels, climate change, and the pressing need for sustainable energy systems, PEMFCs have become a viable alternative. PEMFCs work on the basis of electrochemical energy conversion, in which hydrogen and oxygen react to produce electricity, with the only by-products being heat and water. This clean energy generation process places PEMFCs as a critical technology in lowering greenhouse gas emissions and addressing climate change (Daud et al., 2017).

The proton exchange membrane (PEM), a thin polymer electrolyte membrane that prevents direct hydrogen and oxygen mixing but allows protons to flow from the anode to the cathode, is the fundamental part of a PEMFC. Electrodes made of platinum are used to catalyze the electrochemical reactions that occur inside the PEMFC. Protons and electrons are released during the oxidation process of the supplied hydrogen at the anode. While the electrons move through an external circuit to create an electric current, the protons move through the PEM to the cathode (Linden et al., 2023). Water is created at the cathode when oxygen molecules mix with protons and electrons.

Because of their low working temperatures (usually between 60°C and 80°C), high power density, and quick start-up times, PEMFCs are especially well-suited for a variety of applications. These qualities make them perfect for use in stationary power generating, portable power devices, and transportation. Furthermore, PEMFCs have attracted a lot of interest from the automotive sector as a possible substitute for internal combustion engines

(ICEs) in cars since they can drastically lower pollution and a vehicle's dependency on fossil fuels (Pollet et al., 2019).

Hou et al., (2024) introduced a significant progress has been made in enhancing the proton conductivity of PEMs, optimizing catalyst design, and improving the overall efficiency of fuel cell systems. Despite these advancements, several challenges remain, particularly in terms of achieving the maximum theoretical efficiency of PEMFCs under real-world operating conditions. Advances in materials science, catalysis, and system integration have driven the development and commercialization of PEMFCs. Researchers have focused on improving the performance, durability, and cost-effectiveness of PEMFCs to enable their widespread adoption. Different stages of the PEM fuel cell development are shown in the table 1.1 (Kirubakaran et al., 2009).

Table 1.1 Different stages of PEMFC development

Stage	Step-wise advancement on fuel cell	Year of Progress
Stage 1	Humphry Davy explains the fuel cell's underlying idea.	1801
	Christian Schonbein published a paper on fuel cell reactions.	1838
	A prototype of the first fuel cell gas voltaic battery was created by William Grove.	1842
Stage 2	Grove's invention was improved by Charles Langer and Ludwig Mond, who gave it the term fuel cell.	1889
	The alkaline fuel cell was first created by Francis Bacon.	1932
	The proton exchange membrane fuel cell (PEMFC) was created by General Electric.	1959

Stage 3	NASA first used fuel cells in space mission	1960
	DuPont developed Nafion.	1960
	General Motors used fuel cell technology in production of the electro van	1966
	An alternative energy technology was developed as a result of the oil crisis.	1970
Stage 4	The United State Navy first used the fuel cell in submarine	1980
	The small stationary fuel cells developed for commercial locations	1990
	Fuel cell were employed in vehicles	2000
	Toyota introduced first commercial fuel cell in car	2014

1.1.2 Advantages of PEMFCs over traditional internal combustion engines

PEMFCs have the potential to displace internal combustion engines (ICEs) in the transportation sector due to their many advantages, especially when it comes to energy efficiency and environmental sustainability which includes:

i) Environmental Impact: One of the biggest benefits of PEMFCs over ICEs is their near-zero emissions when producing electricity. Unlike ICEs, which release harmful pollutants like particulate matter, carbon dioxide (CO₂), and nitrogen oxides (NO_x), PEMFCs only release water vapour and heat as by-products. This makes them an environmentally friendly alternative, especially when it comes to environmental sustainability and energy efficiency (Cooper et al., 2004).

ii) Energy Efficiency: Braga et al., (2014) introduced a remarkable demonstration regarding energy efficiency of PEMFCs over ICEs. When it comes to turning hydrogen into electricity, PEMFCs can attain efficiencies of up to 60%, while ICEs normally have thermal efficiencies

of between 25% and 30%. PEMFCs have an overall efficiency of more than 80% when used in combined heat and power (CHP) systems because the heat produced during the electrochemical reaction may be collected for use. Because of its great efficiency, there is a decrease in both fuel consumption and overall running expenses.

iii) Silent Operation: Gencoglu et al., (2009) design PEMFCs for residential application which makes them appropriate for use in portable power devices and home power production applications where noise reduction is a priority. PEMFCs operate quietly because, aside from auxiliary equipment like pumps and fans, they don't have any moving parts. On the other hand, ICEs are notorious for producing a lot of noise, which can contribute to noise pollution, especially in cities.

iv) Fuel Flexibility: PEMFCs run mostly on hydrogen, which can be generated from biomass, natural gas, water electrolysis, and other sources. This fuel sourcing flexibility is a big plus because it makes it possible to use renewable energy sources to generate hydrogen, which further improves the environmental benefits of PEMFCs. PEMFCs can also run on reformed hydrocarbons, but this requires additional processing to get rid of contaminants like carbon monoxide (CO), which can damage the fuel cell catalyst (Cai et al., 2024).

v) Modularity and Scalability: PEMFCs are very scalable, allowing them to be adjusted in size to match the unique power needs of various applications. They may be used for a variety of tasks, from big stationary power plants to tiny portable devices, because to their scalability (Ogbonnaya et al., 2020). PEMFCs' modular design makes it easier to integrate them into hybrid systems, where they can complement super capacitors or batteries to offer the best performance under a variety of operating circumstances.

vi) Safety and Reliability: PEMFCs offer several advantages in terms of safety, which is a crucial component of energy systems. Hydrogen is the primary fuel for PEMFCs because it has a higher energy density per mass unit than traditional fuels like petrol or diesel. Although hydrogen is very flammable, PEMFC systems are built with safety elements to reduce risks, such as strong enclosure systems and leak detection sensors. Additionally, the relatively simple mechanical design of PEMFCs improves their reliability by reducing the likelihood of mechanical failures (Vasilyev et al., 2021).

vii) Future Prospects: Governments, businesses, and academic institutions all around the world are beginning to acknowledge that PEMFCs have the potential to help ensure a sustainable energy future. In order to reach net-zero emissions targets, PEMFCs are anticipated to be essential as efforts to decarbonize the energy sector increase. Wang et al., (2017) demonstrate how PEMFC usage in a number of industries, including transportation, industrial processes, and household energy systems, is anticipated to accelerate due to developments in fuel cell technology and hydrogen production, distribution, and storage innovations. However, PEMFC is not utilised worldwide because of its insufficient endurance. The difficulty of optimising PEMFC efficiency is covered in the next section.

1.1.3 Challenges in maximizing PEMFC efficiency

Although PEMFCs have many established benefits, realizing their full theoretical efficiency in practical applications is still a major hurdle. Numerous factors, such as the management of hydrogen and oxygen flow, catalyst degradation, fuel cell component durability, water and heat management and thermal management contribute to this efficiency difference in PEMFCs are mention below:

i) Hydrogen and Oxygen Flow Management: Appropriate control of the flow rates of hydrogen and oxygen is critical to PEMFC efficiency. Different flow rates might cause reactants to be distributed unevenly across the fuel cell, which can leave some areas of the cell functioning less than optimally. Reactant local hunger may result from this, lowering efficiency and power output. Fan et al., (2021) presented ineffective flow control can make problems with flooding and dry-out worse, which can harm the fuel cell and shorten its lifespan.

- Flooding: The accumulation of surplus water generated at the cathode within the fuel cell causes flooding, which obstructs the gas diffusion layer (GDL) and restricts oxygen's ability to reach the catalyst sites. Performance may suffer as a result, and the oxygen reduction reaction's (ORR) efficiency may be severely reduced. Van et al., (2021) show that efficiency in water management is essential to maintaining fuel cell performance and preventing floods.
- Conversely, low water content in the PEM can cause dry-out conditions, which cause the membrane to become dehydrated and lose its ability to transmit protons. This can harm the membrane irreversibly in addition to lowering the fuel cell's efficiency. Optimizing the hydration state of the PEM is essential for extending the lifespan and effectiveness of PEMFCs (Ziane et al., 2023).

ii) Catalyst Degradation: The electrochemical reactions at the anode and cathode in PEMFCs are aided by the catalyst layer, which is usually made of platinum or platinum alloys. The efficiency and longevity of PEMFCs, however, might be severely impacted by the substantial obstacle of catalyst degradation over time (Prokop et al., 2020). Among the elements causing catalyst deterioration are:

- **Carbon Corrosion:** The catalyst is frequently supported by carbon materials, which are susceptible to corrosion in specific working environments, especially during cycles of startup and shutdown. The efficiency of the fuel cell is reduced due to the loss of catalyst particles and a decrease in active surface area caused by carbon corrosion.
- **Platinum Dissolution and Migration:** Under high voltage circumstances, platinum catalysts are prone to dissolution and migration within the fuel cell. Over time, performance may deteriorate as a result of platinum particle agglomeration and decreased catalytic activity.

iii) **Membrane Durability:** The proton exchange membrane is a critical component of the PEMFC, responsible for conducting protons from the anode to the cathode. The durability of the membrane is a key factor in determining the overall lifespan of the fuel cell. Several challenges related to membrane durability include:

- Chemical and mechanical degradation are both possible. Wan et al., (2022) illustrate Chemical degradation is primarily caused by reactive oxygen species (ROS) that are produced during electrochemical reactions. ROS can attack the membrane's polymer structure, causing a loss of proton conductivity and decreased fuel cell performance. Mechanical degradation is caused by changes in temperature, humidity, and pressure during operation. Over time, these stresses can lead to the formation of cracks and pinholes in the membrane, resulting in gas crossover and reduced efficiency.

iv) **Thermal Management:** To keep PEMFCs working at their ideal temperature, thermal management must be done effectively. Thermal gradients created by the fuel cell's excessive heat output during operation may cause components to expand and contract unevenly. This may lead to mechanical strains and a decrease in the fuel cell's longevity. High temperatures

can also hasten the chemical breakdown of membranes and catalysts. On the other hand, running the fuel cell at temperatures below its ideal range can lower its reaction rates and overall efficiency (Cozzolino et al., 2022).

v) System Integration and Balance of Plant (BoP): Wu et al., (2020) describe that optimizing PEMFC performance and lifespan requires effective system integration. The systems for supplying hydrogen and oxygen, humidifiers, cooling systems, and power electronics are examples of Balance of Plant (BoP) components. These systems are crucial in preserving the fuel cell stack's ideal operating conditions. The smooth integration and functioning of these parts are critical to the overall PEMFC system's efficiency.

- **Hydrogen supply and storage:** The effectiveness of PEMFCs depends on the effective supply and storage of hydrogen. To provide a steady and dependable fuel supply, issues with hydrogen storage, such as volumetric density and safety problems, must be resolved. The hydrogen delivery system must also be designed to minimize pressure drops and guarantee that hydrogen is distributed uniformly to the anode (Hai et al., 2024).
- **Cooling and thermal management:** To keep the PEMFC stack from overheating and to keep it at the ideal operating temperature, the cooling system must efficiently disperse the heat produced during the electrochemical reactions. Ensuring a consistent temperature distribution throughout the fuel cell is crucial for the design of the cooling system, since thermal gradients can result in decreased durability and mechanical strains (Xu et al., 2022)
- **Power electronics:** The power electronics, including DC-DC converters and inverters, are responsible for conditioning the electrical output of the PEMFC to meet the

specific requirements of the application. The efficiency of the power electronics directly impacts the overall efficiency of the PEMFC system. Additionally, the power electronics must be designed to handle the dynamic response of the PEMFC to varying load conditions while minimizing losses. Choe et al., (2008) created a dynamic simulator for a PEM fuel cell system that uses a PWM DC/DC converter.

vi) Scalability and cost: The scalability and cost-effectiveness of PEMFC technology is one of the main obstacles to their wider adoption. Despite all of PEMFCs' benefits, their high cost continues to be a major obstacle to commercialization. The usage of pricey components like high-performance proton exchange membranes and platinum catalysts drives up the cost of PEMFCs. The development of substitute catalysts, cost reduction of these materials, and production process optimization are essential for PEMFC commercial viability.

- Catalyst cost reduction: One of the main sources of costs in PEMFCs is the catalyst, which is made of platinum. Alternative catalysts, like platinum alloys and catalysts made of non-precious metals are being developed in an effort to reduce costs and increase availability. Furthermore, lowering the total cost of the fuel cell is possible by increasing the usage of platinum through improved catalyst design and distribution.
- Durability and cost of the membrane: Pandiyan et al., (2013) illustrate another important component that affects the total cost of PEMFCs is the cost of the proton exchange membrane. The goal of research is to create more affordable and long-lasting membranes that can sustain high proton conductivity under the demanding working conditions of PEMFCs. Technological developments in membranes, like the creation of composite membranes and the application of new materials, have the potential to lower PEMFC costs and increase their longevity.

- Production and assembly: To guarantee the efficiency and dependability of the fuel cell stack, PEMFC production and assembly procedures are intricate and highly precise. Simplifying these procedures and using automated manufacturing methods can lower PEMFC production costs and enable wider distribution of these devices.

vii) Durability and lifespan of PEMFC: The lifetime and durability of PEMFCs are crucial factors in determining whether or not they are suitable for a variety of applications, particularly in the automotive and stationary power sectors. In order to achieve a long lifespan with excellent performance, the deterioration mechanisms of the fuel cell components must be addressed. Accelerated stress testing and innovative materials are essential for enhancing fuel cell durability.

- Accelerated stress testing: In order to quickly produce degradation in a proton exchange membrane fuel cell (PEMFC), a laboratory technique known as "accelerated stress testing" (AST) purposefully provides harsh working conditions to a PEMFC in a little amount of time (Colombo et al., 2023). By understanding the degradation mechanisms, researchers can develop mitigation strategies and improve PEMFC durability.
- Material innovations: To increase the robustness and longevity of PEMFCs, advances in materials science are necessary. Examples of these advancements include the creation of stronger catalysts, membranes, and gas diffusion layers. (Lee et al., 2022) These developments may lessen the effects of thermal, chemical, and mechanical stressors on the fuel cell's constituent parts.

viii) Environmental and safety considerations: Although PEMFCs have a great deal to offer the environment, there are safety and environmental issues that come with their extensive

use. Important factors to take into account include the safe generation, handling, and storage of hydrogen as well as the disposal of PEMFC components.

- Safety of hydrogen: Because hydrogen is a highly combustible gas, PEMFC systems must handle and store it safely. Strict safety regulations must be followed in the design of hydrogen storage tanks, fuel lines, and safety systems in order to stop leaks and reduce the chance of explosions (Gerbec et al., 2008).
- Component recycling: With the growing use of PEMFCs, it will be more crucial than ever to dispose of and recycle fuel cell components including catalysts and membranes. The long-term success of PEMFCs depends on the development of sustainable recycling technologies that reduce environmental effect while recovering valuable materials.

ix) Trends in Research and Development: PEMFC technology's future depends on ongoing study and development to overcome the obstacles and constraints mentioned above.

Important areas of attention consist of:

- Innovative materials: Lee et al., (2022) explain how the next generation of PEMFCs depends on the development of innovative materials with improved qualities, such as increased endurance, better thermal stability, and stronger proton conductivity.
- System integration: To build sustainable and effective energy systems, research into the integration of PEMFCs with renewable energy sources, such solar and wind, is crucial. Furthermore, the creation of hybrid systems that integrate PEMFCs with super capacitors or batteries can improve the efficiency and adaptability of PEMFCs in a range of applications.
- Cost-reduction strategies: To make the technology commercially feasible, ongoing attempts to lower the cost of PEMFCs through material innovation, process

optimization, and economies of scale are crucial. Cost-cutting initiatives will be mostly driven by corporate alliances, government subsidies, and research funding.

- International collaboration: International cooperation between academics, business, and governments will be beneficial to the development and commercialization of PEMFC technology. Global PEMFC technology acceptance and advancement can be accelerated by pooling resources, knowledge, and skills.

1.2 Problem statement

1.2.1 Issues related to flow and pressure management in PEMFCs

PEMFCs, or proton exchange membrane fuel cells, are a potential new technology in clean and efficient energy production, especially for stationary power generation and transportation applications. Nonetheless, a number of difficulties with controlling pressure and flow within the PEMFC stack restrict its effectiveness, longevity, and performance (Lu et al., 2019). The complex interactions between the fluidic, thermal, and mechanical systems that enable the electrochemical reactions inside the fuel cell are the cause of these challenges.

An anode and a cathode divided by a proton exchange membrane (PEM) make up a PEMFC's core. The anode receives hydrogen, which is divided into protons and electrons there. While the electrons move through an external circuit to produce electricity, the protons move through the PEM to the cathode. The cathode receives oxygen, usually in the form of air, which combines with the protons and electrons to produce water. PEMFCs must operate at their best when hydrogen and oxygen flows are efficiently managed. However, two common problems that occur throughout this process are reactant starvation and membrane flooding, which are discussed below.

- Reactant starvation occurs when specific regions of the fuel cell do not receive enough of the required reactants. This can be caused by an inadequate supply of hydrogen or oxygen. This circumstance results in unequal power production and may hasten the catalyst material's deterioration (Chen et al., 2019).
- Flooding: An excessive amount of water may be produced inside the cell when the flow of hydrogen or oxygen is not adequately regulated, resulting in the phenomena known as flooding. The fuel cell's overall performance declines as a result of flooding, which also narrows the effective response area, increases mass transport resistance, and obstructs the flow channels.

1.2.2 Difficulties with pressure regulation

Sustaining the proper pressure levels inside a PEMFC is essential to its longevity and functionality. The mechanical integrity of the fuel cell components is influenced by the reactant gas pressure in addition to the reaction rates are mentioned below:

- Pressure difference management: Controlling the pressure difference across the membrane in PEMFCs is one of the biggest problems. A significant difference may result in mechanical strains that distort or even tear the membrane. The fuel cell's lifespan may be significantly shortened by this mechanical breakdown.
- Impact on water management: The water balance inside the cell is directly impacted by the reactant pressure. Low pressure may impede the efficient evacuation of water, raising the risk of flooding, whereas high pressure on the cathode side may encourage the back-diffusion of water to the anode, resulting in membrane dehydration (Wang et al.,2024).
- Reaction rate sensitivity: The pressure of the hydrogen and oxygen in a PEMFC has a significant impact on the rate of electrochemical reactions. In general, higher

pressures speed up reactions and increase effectiveness. But too much pressure might worsen flooding problems or put too much strain on the membrane, which is why exact pressure control is essential (Søndergaard et al., 2019).

1.3 Adaptive load reaction and membrane stress in transient condition

The common issues that make flow and pressure management more challenging are variable load conditions, membrane stress in transient condition, and transient water dynamics are discussed below:

- **Fluctuating load demands:** Variations in power consumption might cause abrupt shifts in the reactant flow and pressure requirements. For the system to continue operating at peak efficiency, these parameters must be easily adjusted by the system.
- **Transient water dynamics:** The PEMFC's water production and removal can vary under dynamic load circumstances, making it difficult to maintain the precise balance needed to avoid both flooding and drying out.
- **Membrane stress in transient conditions:** The membrane may experience increased mechanical stress as a result of sudden variations in load, which could shorten its operating lifespan or cause mechanical breakdown.

1.3.1 The requirement for better control methods

Advanced control methods that can maximize the flow and pressure management in PEMFCs and therefore improve their performance, stability, and longevity are desperately needed to address the aforementioned issues. The intricate and dynamic interactions within the PEMFC stack are difficult to manage with traditional control methods, which calls for the investigation of more advanced techniques.

1.3.2 Motivation for the research

The necessity for reliable, clean, and efficient energy solutions has been highlighted by the continuous global move toward sustainable energy sources. Proton Exchange Membrane Fuel Cells (PEMFCs) are a viable option among the alternatives because of their high theoretical efficiency, silent operation, and almost negligible emissions. PEMFCs are very appealing for applications ranging from stationary power generation to transportation because of these qualities.

PEMFCs have great potential, but realizing their full theoretical efficiency in real-world applications is extremely difficult. Significant challenges are presented by the complex flow and pressure management dynamics inside the PEMFC stack, which frequently result in problems including flooding, membrane dehydration, catalyst deterioration, and overall efficiency losses.

The urgent need to resolve these issues and realize PEMFCs' full potential as a crucial technology in the global energy transition is what drives this research. Conventional control techniques have not been able to effectively handle the intricate relationships that reactant flow, pressure, and dynamic load conditions have within PEMFCs. The investigation of more advanced control methods, in particular fractional-order controllers (Petráš 2012), which provide more flexibility and accuracy in controlling the dynamic behaviour of PEMFCs, has been spurred by this deficiency.

The goal of this research is to close the gap between PEMFC performance in practice and theoretical efficiency. The goal of this effort is to overcome the drawbacks of current methods and open the door to more durable, effective, and dependable PEMFC systems by creating and verifying sophisticated control strategies including fractional PI/D controllers and

optimization programs. The ultimate objective is to support the wider application of PEMFC technology, enabling the development of a more sustainable and clean energy environment for coming generations.

1.3.3 Research gap identified

Even though Proton Exchange Membrane Fuel Cells (PEMFCs) have made great strides and have the potential to be a sustainable energy technology, there are still a number of important research gaps that need to be filled. These gaps are especially noticeable in the domains of optimization approaches, control strategies, and flow and pressure management—all of which are critical to optimizing PEMFC system performance and efficiency. In this study, the following gaps are identified for the modelling, control and optimization of PEMFC's as mentioned here:

- Flow and Pressure Management Challenges
- Limitations of Conventional Control Methods
- Design and Application of Fractional-Order Controllers
- Comparative Analysis of Various Optimization Techniques

1.4 Research objectives

Technologies that offer clean, efficient, and reliable energy are receiving more attention as a result of the world's rapid shift towards sustainable energy sources. Proton Exchange Membrane Fuel Cells (PEMFCs) are unique among these technologies because of their quiet operation, almost negligible emissions, and high theoretical efficiency. However, problems with flow and pressure control within the fuel cell stack have made it difficult for PEMFCs to reach their full potential in real-world applications. These difficulties highlight the requirement for sophisticated optimization and control methods to improve PEMFC

performance in a range of scenarios. The following research objectives are designed to develop and implement novel control strategies and optimize PEMFC performance under various operating situations in order to overcome these problems.

1.4.1 Development of advanced control strategies using fractional order controller

The main goal of this research is to create and apply sophisticated control schemes that take advantage of the special benefits of fractional-order controllers for PEMFC systems. When it comes to managing intricate, dynamic systems like PEMFCs, fractional-order controllers—in particular, the fractional PID (FOPID) controllers—offers a greater degree of flexibility and precision. Fractional-order controllers, as opposed to conventional integer-order controllers, include non-integer order derivatives and integrals, enabling more intricate control over the dynamic behaviour of the system.

- An extensive investigation of the foundations of fractional-order controllers opens the study. This includes being aware of fractional calculus's mathematical underpinnings and how control system design can benefit from using them. The study will look into the particular characteristics of fractional-order controllers, such as their capacity to offer improved control over systems with extended memory or inherited characteristics that make them appropriate for PEMFC applications. The goal of the research is to fully comprehend these characteristics in order to customize fractional-order controllers to the unique requirements of PEMFC systems.
- The next stage is to create a fractional-order PID (FOPID) controller especially for PEMFC systems, building on the fundamental knowledge of fractional-order controllers. The PEMFC stack's intricate flow and pressure dynamics will be managed by the FOPID controller, guaranteeing reliable and effective operation in a range of scenarios. To attain the intended control performance, the design process will entail

choosing suitable values for the fractional orders (λ and μ) and fine-tuning parameters. The controller's capacity to manage nonlinearities, disturbances, and uncertainties in the PEMFC system will receive particular focus (Khazali et al., 2013).

- Following design, the FOPID controller will be put into use in a PEMFC simulation environment. In this step, a comprehensive simulation model of the PEMFC system is created, taking into account important variables including load fluctuations, pressure dynamics, and the flow rates of hydrogen and oxygen. The FOPID controller will be thoroughly tested and validated in the simulation environment, giving insights into how it functions in various operational circumstances. The aim is to guarantee that the controller can sustain maximum efficiency, limit overshoot, shorten reaction times, and improve overall PEMFC system stability.

1.4.2 Improving PEMFC efficiency under different operating condition

Optimizing PEMFC performance under various operating settings and disturbances is the second main goal of this research. Variations in the supply of hydrogen and oxygen, as well as other external disturbances, can have a negative impact on the operation of PEMFCs. It is essential to create optimization algorithms that can adjust to these differences and maintain optimal performance in order to guarantee reliable and effective operation.

- Following the identification of the critical elements influencing PEMFC performance, the research will create optimization strategies utilizing cutting-edge algorithms. The FOPID controller's parameters will be adjusted as part of the optimization process to provide the optimal performance under various circumstances. To optimize the controller parameters, methods like Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and Genetic Algorithms (GA) will be used. The selection of

these algorithms is based on their capacity to effectively explore extensive parameter spaces and identify ideal solutions in intricate, nonlinear systems.

- The optimized FOPID controller will be tested, and its performance will be compared to that of traditional optimization techniques. This comparative analysis will assess the benefits and drawbacks of the suggested optimization strategies, emphasizing the unique enhancements provided by sophisticated algorithms such as GA, PSO, and GWO. The research intends to support the implementation of the suggested solutions in future PEMFC systems by presenting a clear comparison and demonstrating their superiority in maximizing PEMFC performance.

1.5 Scope and significant

1.5.1 Overview and scope of the research

The goal of this research is to improve the performance of proton exchange membrane fuel cells (PEMFCs) by the invention and application of sophisticated control systems. The major objective is to tackle the difficulties associated with managing flow and pressure in PEMFC systems, which are essential for preserving stability and efficiency in a range of operating scenarios. In order to give more accurate and flexible control over the dynamic behaviour of PEMFCs, the research makes use of fractional-order controllers, specifically fractional-order PID (FOPID) controllers.

This study's scope includes several important areas:

- The study will investigate the theoretical underpinnings and real-world applications of fractional-order control, with a particular emphasis on how these controllers might be customized to meet the unique requirements of PEMFC systems.

- **Optimization of PEMFC Performance:** To improve the performance of the fractional-order controllers. Gul et al, (2021) explain how to apply optimization strategies including Genetic technologies (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO) to calculate the essential parameter for any dynamical system. These methods will be used to optimize the control settings in the face of changing circumstances and disruptions, guaranteeing reliable and effective PEMFC performance.
- **Simulation and Validation:** To verify the efficacy of the suggested control schemes and optimization methods, a number of in-depth simulations will be run.
- **Comparative Analysis:** To illustrate the enhancements and benefits provided by the suggested methodologies, the performance of the optimization techniques and the fractional-order controllers will be compared with conventional control methods.

1.5.2 Importance of fractional-order control in Improving PEMFC efficiency

Offering distinct benefits above conventional integer-order controllers, fractional-order control is a noteworthy development in the field of control systems. Fractional-order controllers are an effective tool for obtaining higher performance in PEMFCs, where precise control over pressure and flow is essential for efficiency.

- **Improved Control Precision:** Non-integer order derivatives and integrals are incorporated by fractional-order controllers, enabling more accurate control system tuning. The additional adaptability is especially helpful in handling the intricate and nonlinear dynamics of PEMFC systems, since even minor changes in pressure and flow can have a big effect on system performance. Fractional-order controllers can assist in maintaining ideal operating conditions by providing finer control over these

variables, which lowers the possibility of problems like floods or performance deterioration (Taleb et al., 2017)

- **Increased Robustness and Stability:** PEMFCs frequently operate in environments with variable ambient conditions and fluctuating load currents, which can put traditional control systems at risk for instability. In the face of such disruptions, fractional-order controllers are renowned for their exceptional durability and stability. They are especially well suited for PEMFC applications because of their capacity to operate in a greater variety of operational conditions without compromising performance. The PEMFC can maintain a steady power output and avoid the inefficiencies brought on by instability or overshoot thanks to this increased stability, which directly translates into increased efficiency (Qi et al., 2020).
- The possibility of raising PEMFC efficiency is further increased by combining fractional-order control with sophisticated optimization methods. The utilisation of methodologies like GA, PSO, and GWO facilitates the methodical adjustment of control parameters to get optimal performance in a variety of scenarios. These optimization techniques combined with fractional-order control provide a more responsive and adaptive control system that can retain high efficiency while responding to changes in real-time.

1.6 Thesis structure

The research aims, methodology, findings, and conclusions of the study are all methodically addressed in each of the various chapters that make up this thesis. The following provides a synopsis of every chapter:

Chapter 1: Overview

An overview of the research background is given in the first chapter, which also emphasizes the role that proton exchange membrane fuel cells, or PEMFCs, play in the production of sustainable energy. It explains the unique issue statement, highlights the main obstacles to PEMFC regulation, and explores the motivation for the research. A synopsis of the research goals, parameters, and importance finishes the chapter, laying the groundwork for the subsequent in-depth analysis.

Chapter 2: Review of Literature

This chapter examines the corpus of research on PEMFC technology, emphasizing the difficulties in managing flow and pressure and how this effect fuel cell efficiency. It also discusses how control techniques have changed over time, moving from more complex fractional-order controllers to more conventional PID controllers. The literature review explains why this study is necessary and points out gaps in the current research, particularly with regard to the application of fractional-order controllers to PEMFCs.

Chapter 3: Methodology

Chapter 3 discusses the study methodology, which includes the development and use of fractional-order PEMFC controllers. In addition to developing fractional-order dynamic models and applying optimisation algorithms such as Genetic Algorithms (GA), Particle Swarm Optimisation (PSO), and Grey Wolf Optimisation (GWO) in the PEMFC system. The chapter also offers an explanation utilising MATLAB software and details the procedures for validating the recommended control strategies.

Chapter 4: Result and Discussion

The simulation results are shown in this chapter, showing how well the suggested fractional-order controllers work to maximize PEMFC performance. The comparison of the outcomes with those attained by conventional control techniques reveals the gains in efficiency, robustness, and stability. The chapter covers the consequences of these discoveries and provides in-depth evaluations of important performance indicators like overshoot, response time, and efficiency benefits.

Chapter 5: Conclusion and future work

The research's main conclusions and their implications for PEMFC control and optimization are outlined in the last chapter. It explores the study's wider ramifications, evaluates the goals of the investigation and how they were met, and makes recommendations for further research. The chapter also addresses how the suggested control mechanisms might be improved and used to different kinds of fuel cells or related energy systems.

CHAPTER 2

LITERATURE REVIEW

2. Literature Review

The literature on PEMFC models and controllers is reviewed in this chapter. These fields include research on improving the performance of PEMFC systems. This section examines several controller types and fuel cell components that are crucial to comprehending PEMFC dynamics.

2.1 Proton exchange membrane fuel cells (PEMFCs)

The development of PEMFCs is evidence of ongoing efforts to get over the financial and technological obstacles that have traditionally prevented their widespread use. Early PEMFC prototypes were mostly created for niche markets, such space missions, where fuel cells' specific qualities—like their high energy density and dependability—were essential. These early systems' usage was restricted to specialized applications due to their high cost and high technical skill requirements (Baroutaji et al., 2021).

The desire for cleaner energy sources and growing concerns about climate change in the 1990s led to a resurgence of interest in fuel cell technology. Research and development expenditures rose throughout this time, which resulted in notable advancements in PEMFC design, materials, and manufacturing techniques (Daud et al., 2017). A significant advancement in PEMFC technology was brought about by the advent of perfluorosulfonic acid (PFSA) membranes, such as Nafion, which provide enhanced chemical stability, mechanical strength, and proton conductivity.

PEMFC research saw a sharp acceleration at the start of the twenty-first century, with an emphasis on resolving the remaining issues with system integration, durability, and cost. Borup et al., (2020) demonstrate that efficiency and durability of PEMFCs have been greatly increased by developments in catalyst materials, especially the creation of platinum-based and platinum-alloy catalysts. Furthermore, the introduction of high-throughput manufacturing

methods, like automated assembly and roll-to-roll processing, has drastically decreased the cost of producing PEMFCs, advancing the technology toward commercial viability.

The materials employed in a PEMFC's essential parts, including as the membrane, electrodes, catalyst layers, and bipolar plates, have a significant impact on the device's performance. Many studies have been carried out to create and improve these materials over time in order to increase their effectiveness, robustness, and affordability (Rosli et al., 2017).

The proton exchange membrane, which acts as the electrolyte and conducts protons from the anode to the cathode while blocking the crossover of gases, is one of the most important parts of a PEMFC. A significant advancement in PEMFC technology has been the creation of PFSA membranes, such as Nafion, which have excellent mechanical strength, chemical stability, and proton conductivity has found by Curtin et al (2004). Nafion membranes, however, have a few drawbacks, including high working temperatures and decreased conductivity at low humidity levels. They are also costly. In order to provide better performance across a wider range of operating conditions, researchers have recently concentrated on developing alternative membrane materials, such as composite membranes, acid-base membranes, and anion exchange membranes.

The electrochemical processes at the anode and cathode of a PEMFC are aided by the catalyst layers. Since platinum-based catalysts are very active and stable, they have been the preferred option. The high expense of platinum and its vulnerability to impurity poisoning, however, have prompted studies into other catalyst materials. The application of non-precious metal catalysts, such as M-N-C (transition metal-nitrogen-carbon) catalysts, and the creation of innovative catalytic support materials that improve platinum dispersion and usage have both been the subject of recent investigations (He et al., 2019).

Another essential part of PEMFCs are bipolar plates, which act as the fuel cell stack's structural backbone and offer channels for electrical conduction, heat transfer, and gas distribution. Graphite was used to make traditional bipolar plates, but because to their high cost and fragility, other materials, like metal and composite plates, were investigated (Tawfik et al., 2007). Although metal bipolar plates, which are usually composed of titanium or stainless steel, have better electrical conductivity and mechanical strength, they are more prone to corrosion in the PEMFC's acidic environment. In order to increase the longevity of metal bipolar plates, recent research has concentrated on creating coatings and surface treatments that are resistant to corrosion.

Gas diffusion layers (GDLs) are essential because they help remove heat and water while guaranteeing that reactant gases are distributed uniformly to the catalyst layers. To improve water management, GDLs are usually composed of carbon-based materials, such as carbon paper or carbon cloth, and are coated with hydrophobic substances (Williams et al., 2004). In order to enhance mass transport and lower pressure drop, GDL material advancements have concentrated on improving the microstructure and surface characteristics.

Apart from that control systems are essential to the functioning of PEMFCs because they guarantee that the fuel cell runs at its best, resulting in high stability, lifetime, and efficiency. PEMFC systems have long relied on conventional control techniques, such proportional-integral-derivative (PID) control, because of their ease of use and efficiency in controlling important variables like temperature, pressure, and flow rates. PID controllers work by minimizing the error between the intended and actual system outputs by modifying the control inputs. Knospe (2006) describe how PID controller use for adaptation, identification and tuning purpose for academic as well as industry. PEMFCs are fundamentally nonlinear systems with intricate interactions between numerous variables, whereas PID control works

well for linear systems with relatively simple dynamics. Because of this, typical PID control might not always deliver the required degree of performance, especially in the presence of disturbances and changing operating conditions (Swain et.al 2015).

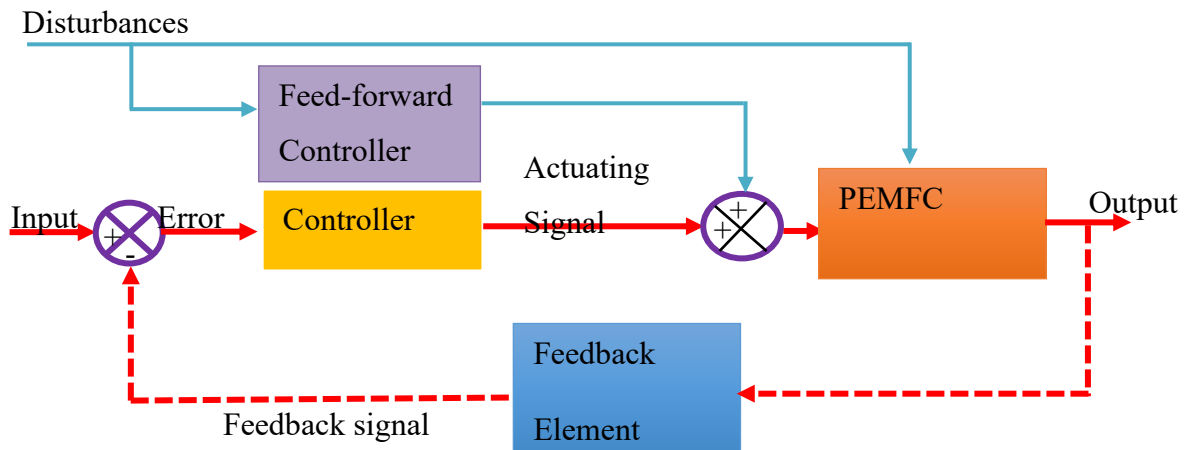


Figure 2.1 Feedback-feed-forward control strategy

A typical closed loop control system with a feed forward controller is illustrated in Figure 2.1. This controller is essentially used to modify the controlled variable (current) prior to its derivative from its set point. When the load is fixed, the traditional closed loop control scheme shown in Figure 2.2 can be helpful.

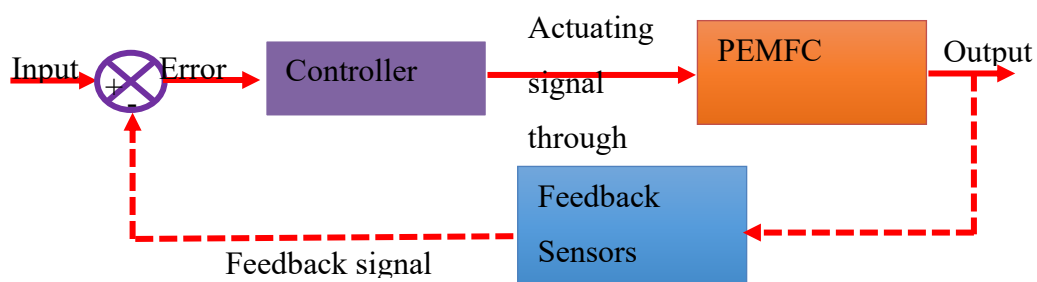


Figure 2.2 State feedback control for PEEMFC

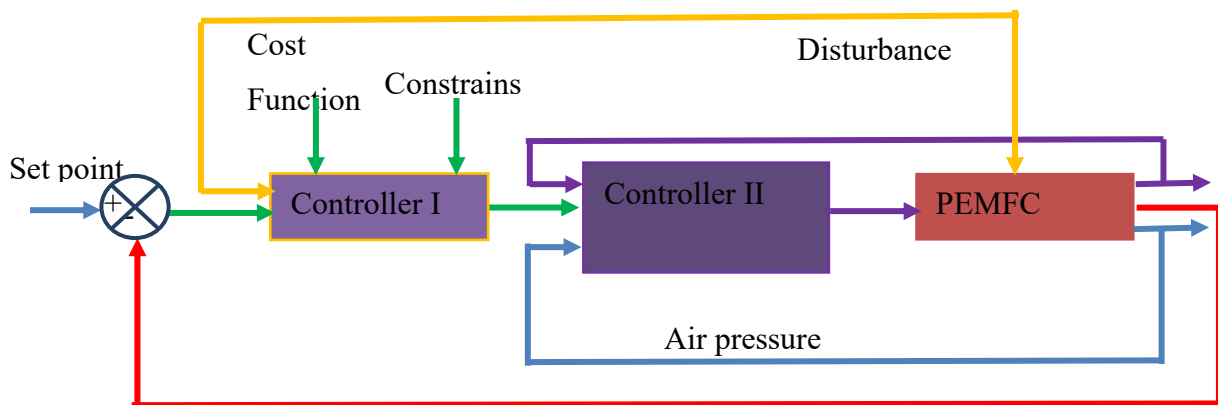


Figure 2.3 A supervisory layer strategy which determines set point to lower loop

A controller for the inner loop and another for the outer loop are shown in Figure 2.3. In this instance, the outer loop's controller output is fed into the inner loop, which in turn produces the system's ultimate controlled output.

Researchers have looked into the application of advanced control systems, such as robust control, adaptive control, and model predictive control (MPC), to get around the drawbacks of conventional PID control. MPC is an effective control method that predicts future behaviour and maximizes control inputs over a limited time horizon by using a mathematical model of the system (Ziogou et al., 2018). Conversely, adaptive control modifies the controller parameters in real-time in response to variations in the dynamics of the system, enabling the controller to continue operating at peak efficiency even in the face of unknowns and disruptions (Zhang et al., 2008).

Fractional-order control, or FOC, has garnered increasing attention for PEMFC systems in recent years. By permitting the derivative and integral actions to be of non-integer order,

fractional-order controllers—like the fractional PID (FOPID) controller—extend the capabilities of conventional PID control. With this extra degree of freedom, the controller's tuning can be adjusted more freely to strike the right balance between robustness, speed of reaction, and stability.

It has been demonstrated that fractional-order controllers are superior to conventional integer-order controllers in a number of ways, especially when it comes to complex dynamics and memory effects. It has been shown that FOC improves the control of important parameters including pressure, temperature, and flow rates in the context of PEMFCs, improving overall performance and efficiency. Furthermore, a number of PEMFC applications, such as load-following, start-up and shut-down control, and fault detection and diagnosis, have effectively used fractional-order controllers. The fractional order PID controller connected to the PEMFC is shown in Figure 2.4.

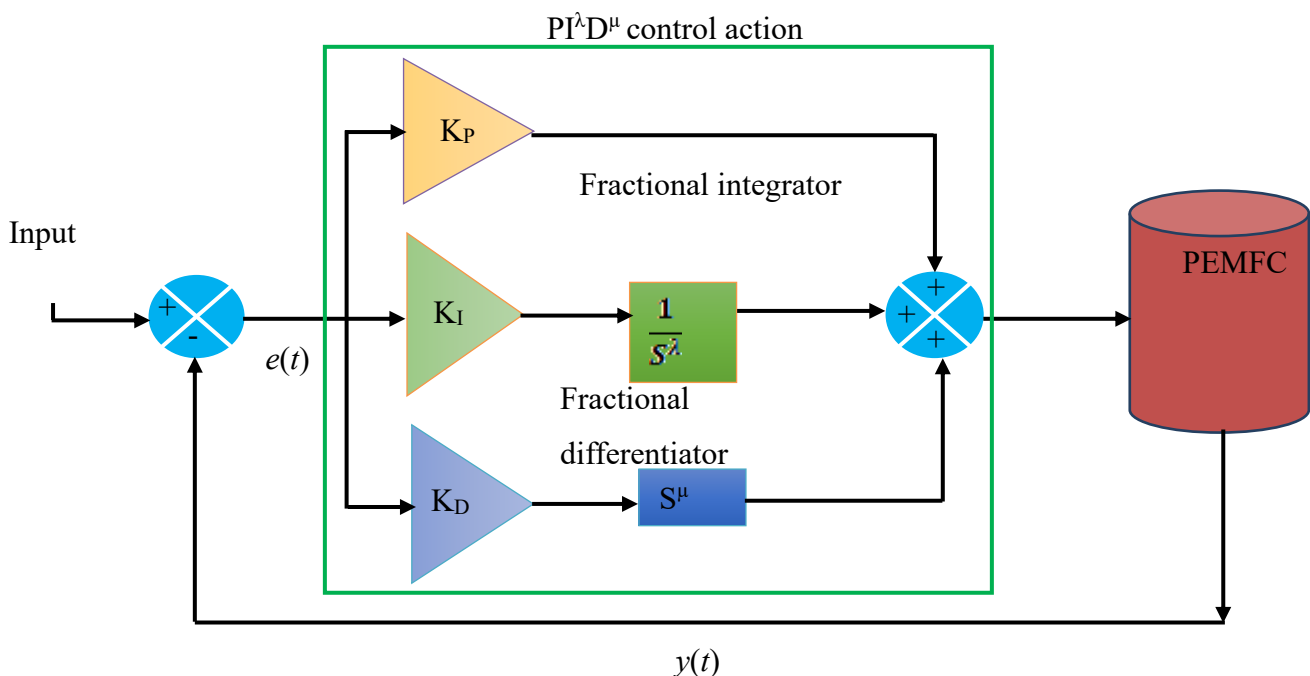


Figure 2.4 Fractional PID block diagram

PEMFC system controller design and tuning is a challenging endeavour that necessitates the optimization of several competing goals, such as decreasing overshoot, settling time, and energy consumption while optimizing robustness and stability. Researchers are increasingly using optimization techniques, like genetic algorithms (GA), particle swarm optimization (PSO), and grey wolf optimization (GWO), to automate the design and tuning process in order to obtain optimal performance(Wilberforce et al 2023).

A subclass of evolutionary algorithms known as genetic algorithms (GAs) simulates natural selection in order to find the best answers within a vast and intricate search space. Due to its versatility in handling restrictions, multi-modal objective functions, and non-linearities, GAs has been extensively utilized in PEMFC system controller design. GAs can effectively search for the ideal set of parameters that minimize a predefined fitness function, such as the integral of absolute error (IAE) or the integral of time-weighted squared error (ITSE), by encoding the controller parameters as chromosomes and evolving them over successive generations. Figure 2.5 illustrates a typical figure in which the fractional PID controller parameter is optimised using a genetic approach.

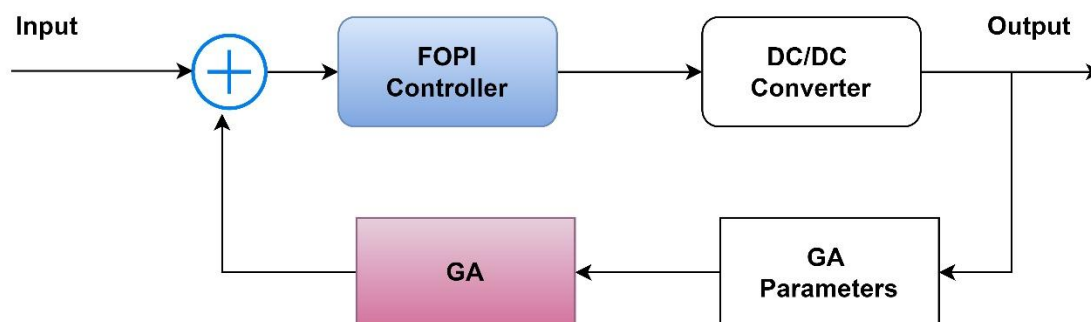


Figure 2.5 GA-FOPI structure

2.1.1 Working principle and operational characteristics

Because of their excellent efficiency, low operating temperature, and zero emissions, proton exchange membrane fuel cells, or PEMFCs, are among the most promising technologies in the field of clean energy. These features make PEMFCs suitable for a variety of uses, such as transportation, portable power systems, and stationary power generation. The electrochemical reaction that transforms hydrogen's chemical energy into electrical energy is the underlying mechanism behind the operation of the PEMFC. Although the idea behind this process is straightforward, it actually requires careful condition control and a number of complex procedures to operate at peak efficiency.

The polymer electrolyte membrane, or proton exchange membrane (PEM), is the central component of the PEMFC. This membrane is a thin, permeable film that is impervious to electrons and gases like oxygen and hydrogen but permits protons, or hydrogen ions, to pass through. A perfluorosulfonic acid polymer, like Nafion, is typically used to make PEMs because of its exceptional chemical stability and proton conductivity. The fuel cell's ability to function depends on the membrane's capacity to conduct protons while obstructing gasses and electrons.

Providing hydrogen gas to the fuel cell's anode side initiates the fundamental functioning of a photovoltaic fuel cell. A catalyst, usually platinum, is applied to the anode to help convert hydrogen molecules into protons and electrons. An illustration of the chemical process at the anode might be:



Every hydrogen molecule is divided into two protons (H^+) and two electrons (e^-) in this instance. The electrons are then transmitted through an external circuit to produce an electric

current, while the protons are able to go through the proton exchange membrane and towards the cathode. One can use this current to run an electric motor or charge a battery. Oxygen gas is supplied on the cathode side, where it comes into contact with a catalyst layer. At the cathode, oxygen and protons that have passed through the membrane combine with electrons that have arrived via the external circuit to generate water. The following is a representation of the cathode reaction:



In addition to the water by product, this process is exothermic, meaning it releases heat. In a PEMFC, the general response is as follows:



This procedure demonstrates the main functional features of PEMFCs: the production of water as the sole by-product, the high efficiency of chemical energy conversion to electrical energy, and the generation of manageable heat that may be used in combined heat and power (CHP) applications. Figure 2.6, shows the basic diagram of the PEM fuel cell.

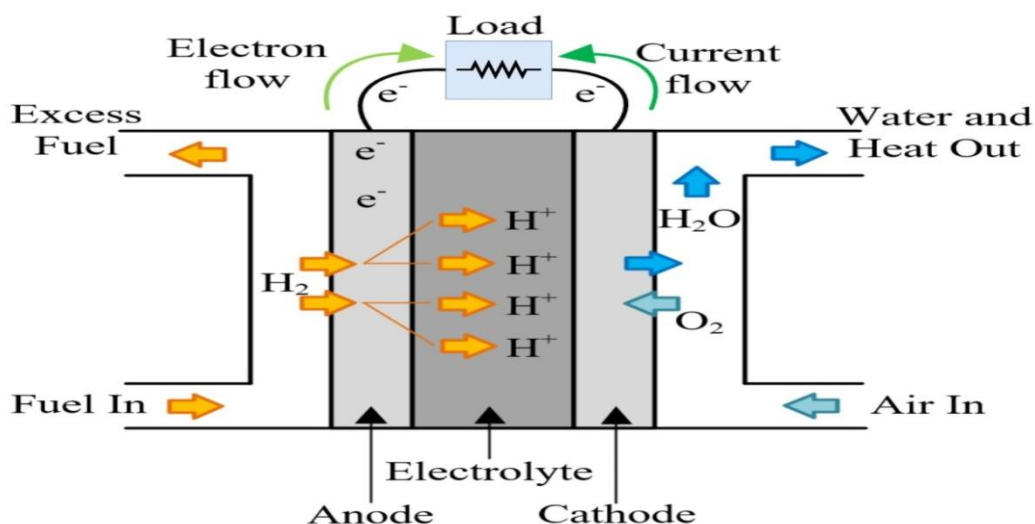


Figure 2.6 PEMC Fuel cell basic diagram

PEMFCs can theoretically achieve efficiencies of about 80%, but in practice, these efficiencies are usually lower because of losses like concentration losses from mass transport constraints, ohmic losses from the resistance of the membrane and other cell components, and activation losses from the energy needed to start the electrochemical reactions. PEMFCs are among the most efficient fuel cell types despite these losses, especially when run in ideal circumstances.

The capacity of PEMFCs to function at low temperatures, usually between 60°C and 80°C, is one of their primary operational features. Because of their low operating temperature, PEMFCs are ideal for use in portable electronics and automobiles where rapid startup and shutdown are crucial. To counteract the slower kinetics of the electrochemical reactions at these temperatures, the catalysts—especially the platinum catalysts utilized at the anode and cathode—must be extremely active when working at these lower temperatures.

Critical operational characteristics of PEMFCs also include their startup and shutdown procedures. In order to protect the fuel cell's membrane and guarantee optimal operation, it is crucial to promptly set the temperature, humidity, and reactant fluxes during startup (Dyanty et al., 2019). Similarly, to avoid catalyst and membrane material damage from reactive oxygen species generation during shutdown, the cell needs to be cleared of reactants, particularly hydrogen.

Another critical component of PEMFC operation is water control. Water is produced by the electrochemical reaction at the cathode and needs to be carefully controlled to avoid flooding the gas diffusion and catalyst layers, which could impede the flow of reactants to the reaction sites (Zhang et al., 2008). The membrane needs to stay adequately hydrated in order to keep its proton conductivity at the same time. The design of the cell's constituent parts and the

operational parameters, such pressure and temperature, are frequently used to control this delicate balance between hydration and water loss.

Another feature of PEMFCs is their scalability. Since individual cells only produce very low voltages (usually about 0.7 V when under load), many cells are linked in series to create a stack that increases the voltage and power output overall. Activation polarisation, ohmic polarisation, and concentration polarisation are the three main types of losses that cause the decline in open-circuit voltage. Consequently, the deviation from the ideal voltage brought on by these polarisations can be used to indicate the cell's operational voltage: Activation polarisation, ohmic polarisation, and concentration polarisation are the three main types of losses that cause the decline in open-circuit voltage. Consequently, the deviation from the ideal voltage brought on by these polarisations can be used to indicate the cell's operational voltage:

$$V(i) = V_{rev} - v_{act_anode} - v_{act_cath} - v_{ohmic} - v_{conc_anode} - v_{conc_cath}$$

Figure 2.7 illustrates how slower electrochemical reaction kinetics at the electrode surface cause activation loss to become more noticeable, especially at larger current demands when the reaction rate finds it difficult to keep up with the current draw. Figure 2.8 show due to increase of temperature activation losses changes drastically.

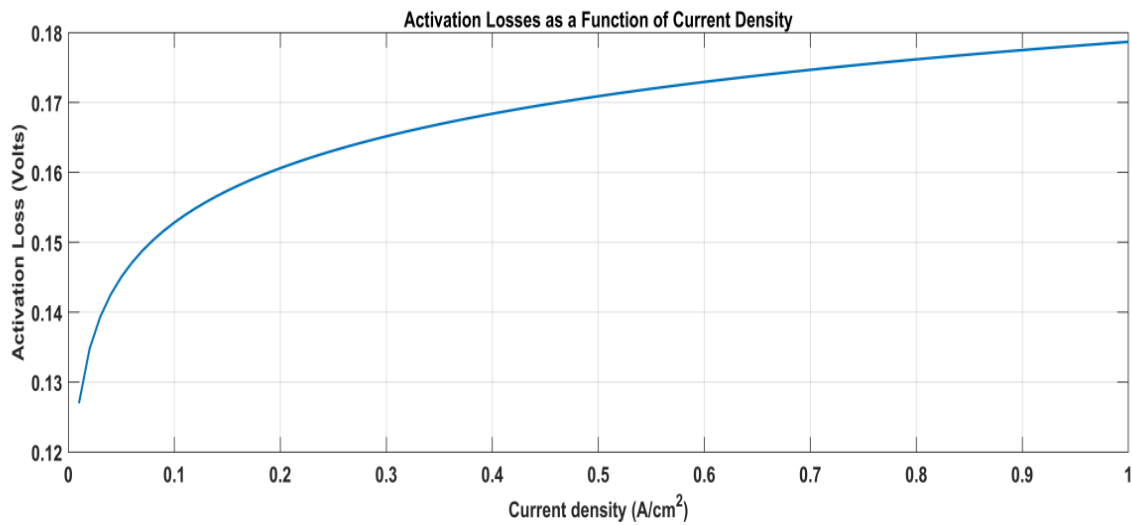


Figure 2.7 Activation losses as a function of current density

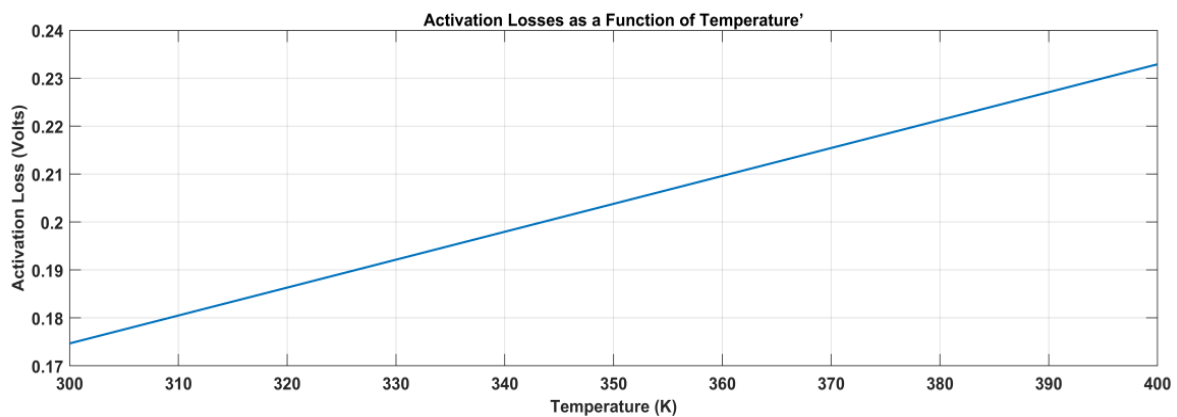


Figure 2.8 Activation losses as a function of current density

The current–voltage, or I–V, curve in figure 2.9 which shows a fuel cell's overall performance under specific operating conditions, is referred to as the polarisation curve. Additionally, it is the most crucial metric for assessing cell performance in typical operating circumstances. Some fundamental data, like peak power density, limiting current density, and open circuit voltage (OCV), can be obtained from the polarisation curve. Figure 2.10 shows how power in fall due the increase load current density. The performance of the fuel cell depends on the hydrogen and air pressure in the fuel cell. The contact resistance may be high and the

reactants are prone to leak if the assembly pressure is too low and the internal cell components are not in close touch. However, excessive pressure is likely to cause damage and overcrowding in the GDL, CL, membrane, or other components, which will increase hydrogen crossover and mass transfer resistance.

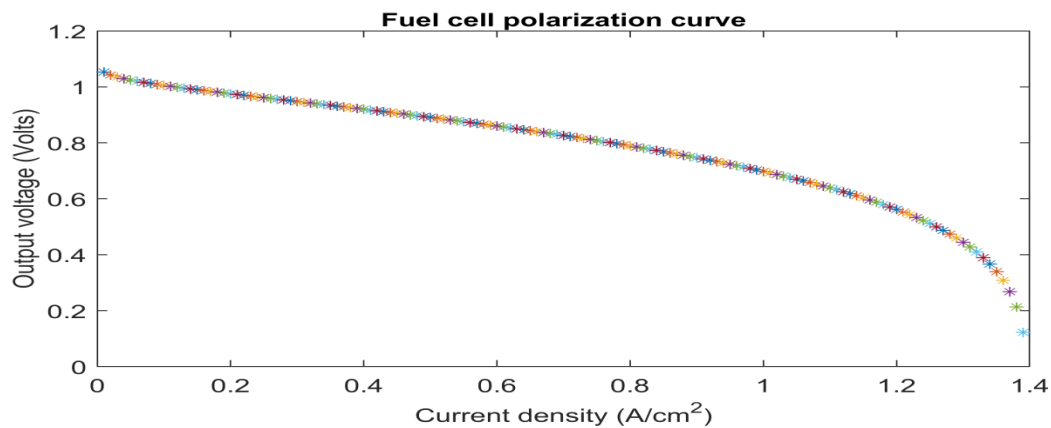


Figure 2.9 PEM fuel cell polarization curve

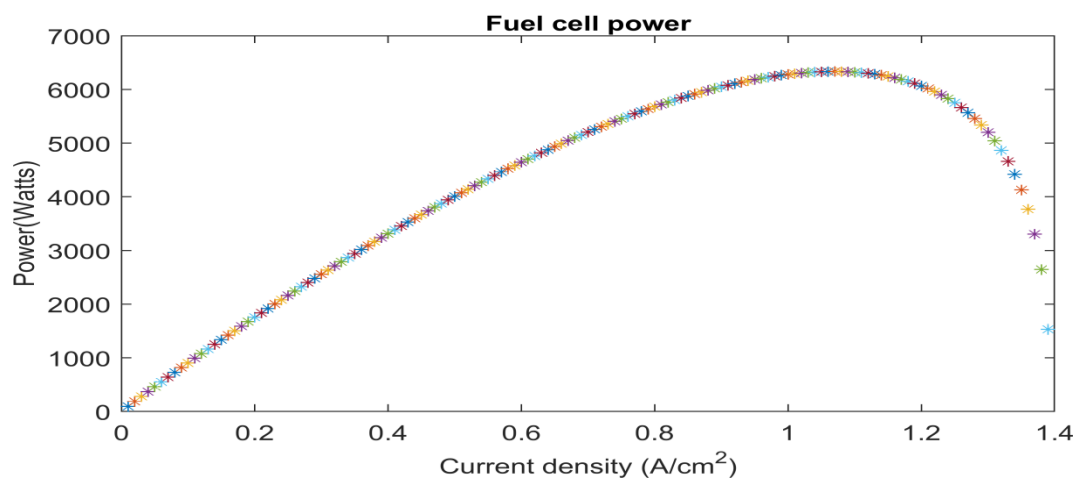


Figure 2.10 PEM fuel cell power curve

PEMFCs' modular design enables power generation to be scaled up or down, from tiny portable power units to massive stationary power plants. PEMFCs have achieved great advancements in terms of lifetime and durability, however problems still exist. Research on the membranes and the catalysts' resilience is crucial, especially when load cycling and stop-

and-start operation are involved (Guo et al., 2021). Carbon corrosion, membrane thinning, and catalyst sintering are examples of degradation mechanisms that can shorten a fuel cell's lifespan and efficiency. To create stronger materials and designs that can prolong PEMFCs' operational life, research is still being done.

All things considered, the operation of PEMFCs relies on a sequence of precisely timed electrochemical reactions made possible by sophisticated materials and meticulous management of operational parameters. High efficiency, low operating temperature, and scalability are among of its operational traits that make them an attractive technology for many different applications.

2.1.2 Key PEMFC components and their Roles

A number of crucial elements must precisely interact for a Proton Exchange Membrane Fuel Cell (PEMFC) to function properly. These elements are all essential to the system's overall performance, longevity, and efficiency. Comprehending the role and significance of these constituents is important for refining PEMFC blueprints and tackling the obstacles that now impede their extensive implementation. The fundamental part of a proton exchange membrane fuel cell (PEMFC) is the membrane which acts as an electrolyte to keep protons from moving from the anode to the cathode while separating the two. The major job of the membrane is to conduct protons while blocking the passage of electrons and gasses. This keeps the reactants apart and guarantees that the ions are moving through the cell in the right direction. The PEM, which is usually composed of perfluorosulfonic acid polymers like Nafion, needs to have a number of essential characteristics, including good hydration management, mechanical strength, low electronic conductivity, strong proton conductivity, and chemical stability. Because the membrane's capacity to transmit protons is highly dependent on its water content, it is imperative to maintain the proper degree of hydration.

The membrane's proton conductivity decreases with excessive drying, increasing ohmic losses and impairing cell performance (Maiyalagan et al., 2010). On the other hand, excessive hydration of the membrane might cause it to enlarge and even break down, which could result in mechanical failure or higher gas crossover and lower efficiency. PEMFC performance is primarily influenced by the gas diffusion layer, membrane thickness, and bipolar plate; these factors' effects are listed below.

2.1.2.1 Layers of Catalysts and membrane thickness

Another crucial element is the membrane's thickness. Although thinner membranes can increase efficiency by lowering the cell's total internal resistance, they also increase the risk of mechanical failure and gas crossover (Lee et al., 2004). Greater durability is provided by thicker membranes, but at the expense of increased resistance and decreased functionality. Because of this, selecting the appropriate membrane thickness requires striking a compromise between longevity and effectiveness, which is determined by the particular application and PEMFC operating parameters.

The PEM must stop hydrogen and oxygen gasses from combining in addition to proton conduction because this could result in direct combustion and possible cell damage. Because of this, the membrane's integrity is essential, and any flaws or pinholes could seriously affect both performance and safety. The PEM's two sides are home to the catalyst layers, which are essential for promoting the electrochemical reactions that produce energy. The platinum catalyst in these layers is usually well distributed and supported by carbon particles, which offer a lot of surface area for the reactions involving the oxidation of hydrogen at the anode and the reduction of oxygen at the cathode (Prass et al., 2021).

The catalyst facilitates the splitting of hydrogen molecules into protons and electrons at the anode due to its relatively high activation energy. After that, the protons travel to the cathode

via the PEM, and the electrons conduct through an external circuit to produce electricity. The catalyst helps reduce oxygen molecules at the cathode, where they combine with protons that have crossed the membrane and electrons that are coming from the external circuit to generate water. This reaction is the fuel cell's rate-limiting step since it usually proceeds more slowly than the hydrogen oxidation reaction. Therefore, in order to reach the appropriate reaction rates, Rajalakshmi et al., (2007) illustrate that the cathode catalyst layer frequently needs more platinum or more active catalyst designs. The dispersion of the catalyst particles, the accessibility of reactants to the catalyst sites, and the elimination of reaction products (such water) from the catalyst layer are some of the variables that affect how effective the catalyst layers. Catalyst poisoning is a serious issue when operating PEMFCs since it can drastically lower the activity of the catalyst, especially when caused by contaminants like carbon monoxide in the hydrogen feed.

The total performance of the PEMFC is also significantly influenced by the porosity and thickness of the catalyst layers. Although thicker catalyst layers might have more reaction-active sites, they might also make mass transport more difficult, especially when it comes to oxygen at the cathode. On the other hand, thinner layers might improve mass transfer at the cost of less catalytic activity. To achieve high performance and efficiency in PEMFCs, it is consequently crucial to optimize the structure and composition of the catalyst layers (Sassin et al., 2019). Figure 2.11 show that due to increase of catalyst thickness ohmic loss is increasing significantly.

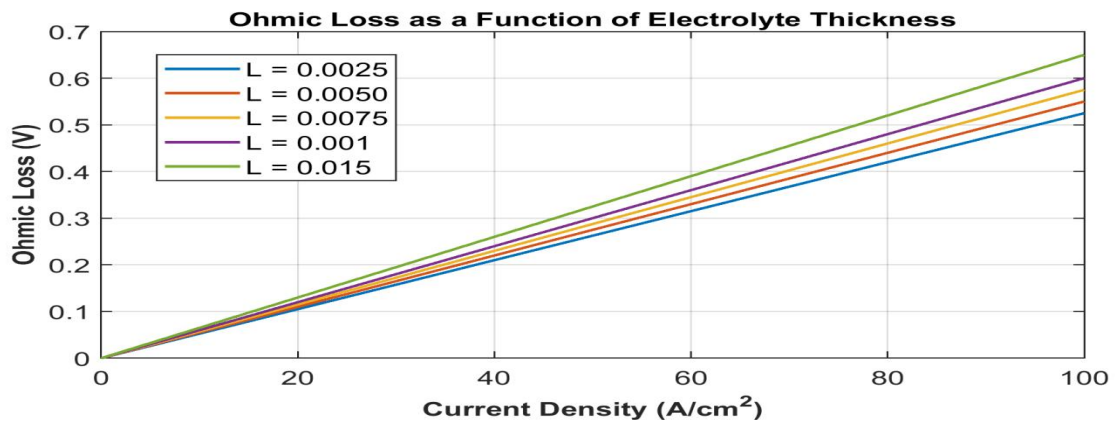


Figure 2.11 Ohmic losses due to layer thickness

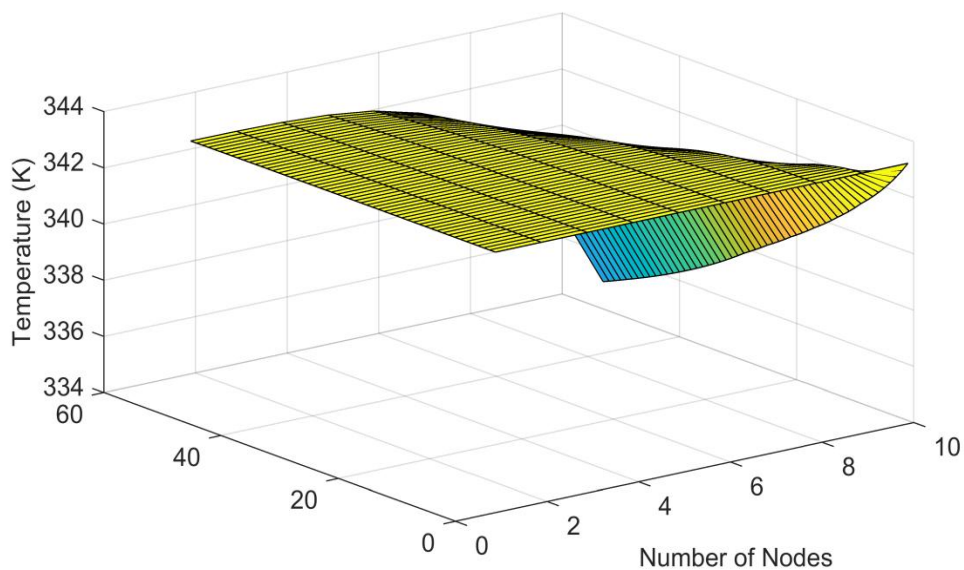
2.1.2.2 Gas diffusion layers (GDLs)

The porous materials known as gas diffusion layers (GDLs) are situated in between the bipolar plates and the catalyst layers. Their main purposes are to help remove water generated at the cathode and to enable the uniform distribution of reactant gases (oxygen and hydrogen) across the catalyst layers.

Carbon-based materials, like carbon cloth or carbon paper, are commonly used to make GDLs because they have adequate porosity to permit gas transport and give strong mechanical strength and electrical conductivity. The GDLs' porosity and thickness are meticulously regulated to guarantee sufficient gas permeability and facilitate the movement of liquid water away from the catalyst layers, so averting flooding. Flooding happens when too much water is generated at the cathode and builds up in the GDL or catalyst layer. This stops reactant gasses from reaching the catalyst sites and lowers the cell's overall efficiency. In order to avoid this, hydrophobic agents—like polytetrafluoroethylene (PTFE)—are frequently applied to the GDLs. PTFE helps to repel water and keep gas diffusion channels open (Han et al., 2008).

The GDLs are involved in heat control in the fuel cell in addition to gas and water management. Heat is produced by the exothermic nature of the electrochemical reactions, and it needs to be effectively drained to avoid overheating and membrane and other component damage. Thus, the GDLs' thermal conductivity plays a role in the PEMFC's overall thermal management. In addition, the GDLs function as electrical conductors, moving electrons produced at the anode to the external circuit and back to the cathode. Therefore, limiting ohmic losses and preserving high overall cell efficiency depend heavily on the electrical conductivity of the GDLs (Spiegel 2011). Figure 2.12 display temperature graphs for each slice after 10 seconds and 120 seconds for the aluminium end plate and polymer end plate, respectively. Figure 2.12(a) shows that, for the polymer, only a little amount of heat has moved to the plate after 10 seconds, whereas the temperature distribution across the aluminium end plate is same after 10 and 120 seconds. These numbers demonstrate that, in contrast to the polymer end plate, heat diffuses through the aluminium end plate more quickly.

(a)



(b)

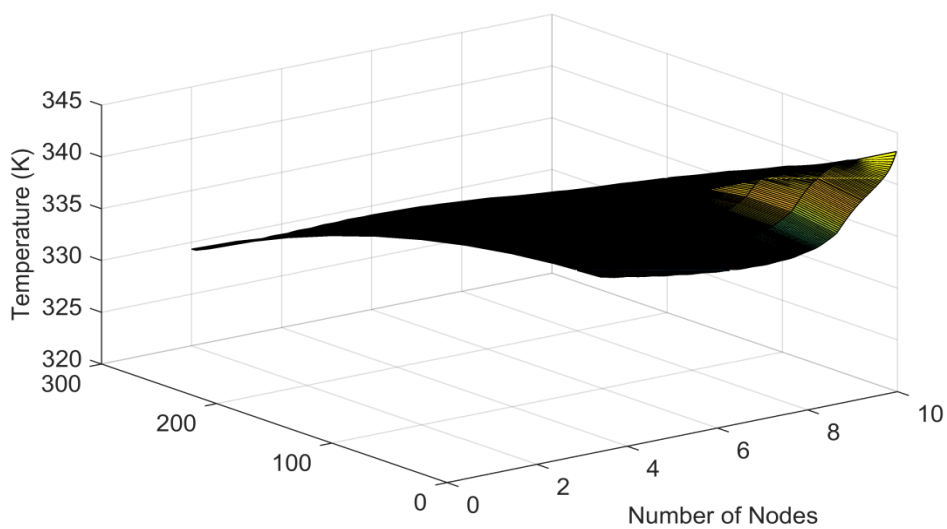


Figure 2.12 The polymer fuel cell plate experiences transient heat conduction at a) 10 second and b) 120 seconds

2.1.2.3 Bipolar plates

Bipolar plates are crucial parts of PEMFC stacks because they perform a variety of tasks that are vital to the fuel cell's overall performance. These plates, which are usually composed of metal, graphite, or composite materials, serve as a means of dividing up the cells within a stack and creating channels for the passage of electrical current between neighbouring cells as well as for the distribution of reactant gasses and product removal.

The bipolar plates' main job is to equally distribute the gasses hydrogen and oxygen across the surfaces of the anode and cathode, respectively. This is made possible by channels that are molded or etched onto the plate surface, directing the gas flow across the catalytic layers and GDLs. For the fuel cell to have uniform gas distribution and to have as little pressure drops as possible, these flow channels' design is essential. Hwang et al., (2013) implemented the best possible balance between efficient gas distribution, water removal, and pressure drop is achieved by utilizing a variety of flow field designs, including serpentine, parallel, and interdigitated patterns.

The bipolar plates are in charge of not only distributing gas but also carrying electrical current produced by fuel cells from one cell's anode to the subsequent cell's cathode in the stack. High electrical conductivity and low contact resistance with the GDLs are necessary for this. Any rise in contact resistance has the potential to cause large ohmic losses, which would lower the fuel cell stack's overall efficiency (Wang et al., 2010).

Managing the heat load produced by the fuel cell during operation is another crucial function of the bipolar plates. The cell's exothermic reactions generate heat, which needs to be efficiently expelled in order to keep the temperature at its ideal level and stop the membrane and other components from deteriorating. Bipolar plates' longevity and resistance to

corrosion are also important factors to take into account, especially in the PEMFC's severe chemical environment, which contains both oxidative and acidic conditions. Although metal plates have advantages in terms of conductivity and mechanical strength, they need to be coated or handled carefully to avoid corrosion, which can contaminate the membrane and catalyst layers and reduce the efficiency of the cell.

The overall design and viability of PEMFC systems are significantly influenced by the weight and cost of the bipolar plates, particularly in automotive applications where economical and lightweight solutions are crucial. Therefore, research and development efforts are concentrated on producing bipolar plates from substitute materials that offer the required performance characteristics but are lighter and less expensive, like lightweight composites or sophisticated coatings.

2.1.2.4 Additional important elements in PEMFC

A PEMFC's performance and operation are influenced by a number of additional components in addition to the main ones covered above. These include the end plates, which apply constant pressure across the stack to ensure good contact between the various layers and prevent gas leaks; the seals and gaskets, which are crucial for preventing gas crossover and preserving the integrity of the fuel cell; and the current collectors, which are used to conduct the electrical current from the bipolar plates to the external circuit. A PEMFC's total performance is the consequence of the meticulous integration and optimization of various parts, all of which have to be made to high standards in order to achieve the right mix of cost, durability, and efficiency. Improvements in PEMFC technology are being driven by advances in materials science, manufacturing processes, and system design, which is moving us closer

to the widespread use of fuel cells as a clean and efficient energy source. The complete details of the component used for PEMFC is shown in the figure 2.13.

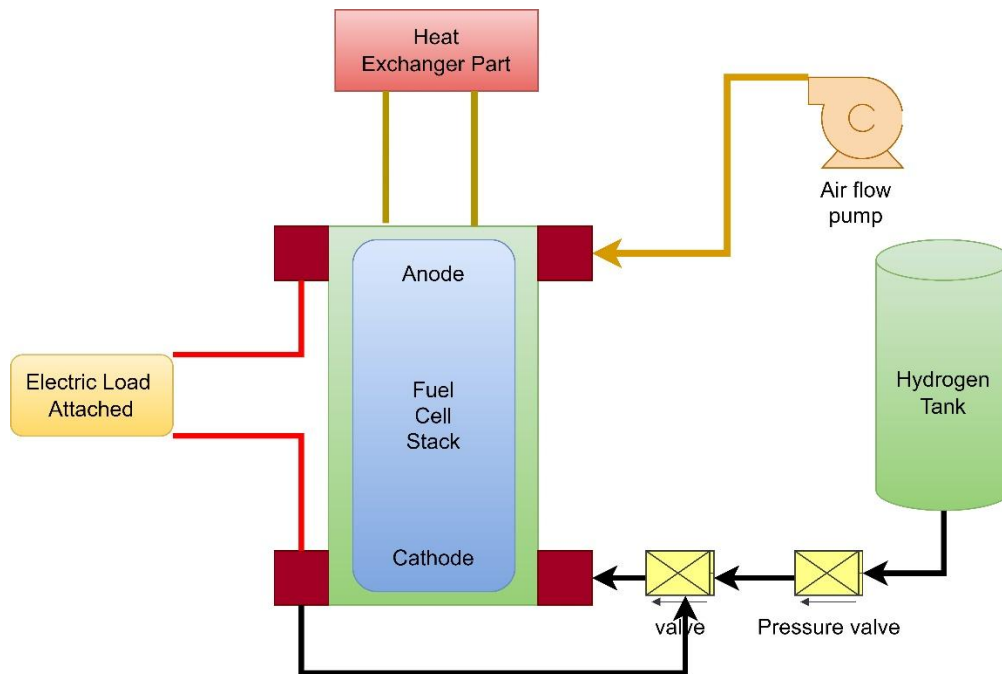


Figure 2.13 Main components of PEMFC (Routh et al., 2024)

2.2 Challenges in PEMFC performance

PEMFCs, or proton exchange membrane fuel cells, have gained traction as a clean and effective energy conversion technology, especially for use in portable electronics, stationary power generation, and transportation. Notwithstanding their benefits, PEMFCs encounter a number of noteworthy obstacles that impede their extensive implementation and effective functioning. Managing the flow of hydrogen and oxygen, as well as the effects of water flooding and pressure fluctuation during the PEMFC operation, are among these challenges that are very important. It is imperative to comprehend and tackle these obstacles in order to maximize the efficiency, robustness, and general feasibility of PEMFC systems.

2.2.1 Issues related to hydrogen and oxygen flow management

The flow of hydrogen and oxygen in a PEMFC must be efficiently controlled to guarantee optimal performance and avoid operational problems. In a PEMFC, the main reactants in the electrochemical processes that produce energy are hydrogen and oxygen. The supply, distribution, or usage of these gasses can be uneven or inefficient, which can result in major performance losses or even damage to the fuel cell's component parts.

The uniform distribution of hydrogen across the anode surface is one of the main challenges associated with hydrogen flow management. Hydrogen molecules are divided into protons and electrons in the anode catalyst layer; this process necessitates a steady supply of hydrogen to all of the active sites in the catalyst layer. Certain parts of the anode may go without hydrogen if the flow of hydrogen is uneven or insufficient, which would result in incomplete reactions and lower power output. Localized hot patches within the fuel cell brought on by hydrogen scarcity may also hasten the deterioration of the catalyst and membrane. The recent research by Bao et al., (2006) and Berg et al., (2004) demonstrate how improper gas distribution inside the gas diffusion layer (GDL), pressure fluctuations within the fuel cell stack, and inadequate design of the flow field channels in the bipolar plates are some of the causes of abnormalities in hydrogen flow. The bipolar plate flow field design is especially important since it controls the flow of hydrogen to the anode. There are benefits and downsides to many designs, including serpentine and parallel flow fields. The design must take into account the requirements for efficient water management, low pressure drop, and uniform gas distribution (Fan et al., 2021).

The distribution of hydrogen is also significantly influenced by the gas diffusion layer (GDL). The GDL has to have enough porosity to provide paths for the elimination of water generated during the electrochemical reaction and to allow hydrogen to permeate uniformly

throughout the anode surface. On the other hand, variations in the porosity and thickness of the GDL may result in areas of hydrogen hunger and an uneven distribution of gas. Furthermore, any build up of water in the GDL can obstruct hydrogen routes, making the issue worse.

The regulation of oxygen flow poses comparable difficulties for the fuel cell's cathode. To guarantee that oxygen, which is usually supplied as air, interacts effectively with the protons and electrons coming from the anode to generate water, oxygen must be distributed evenly throughout the cathode catalyst layer. Any variations in the availability of oxygen can cause oxygen famine in certain places, which would lead to incomplete reactions and lower power output. Reactive oxygen species (ROS), which can deteriorate the catalyst and membrane components and shorten the fuel cell's lifespan overall, can also be produced by oxygen shortage. Since oxygen is less reactive than hydrogen, managing oxygen flow is more difficult and requires more active catalyst sites and better gas distribution to achieve the appropriate reaction rates. Therefore, it is essential to design the cathode flow field and GDL in a way that guarantees oxygen is distributed evenly throughout the catalyst layer. Nitrogen in the air supply can also cause the oxygen concentration to be diluted, which makes controlling oxygen flow much more difficult and lowers the fuel cell's overall efficiency.

Variations in pressure inside the fuel cell stack are also important for controlling the flow of oxygen and hydrogen. To guarantee that both gases are delivered at the best rate for the electrochemical reactions, the pressure of hydrogen and oxygen within the cell should ideally be properly balanced. In actuality, however, variables including altered operating conditions, altered reactant supply, and altered flow field design can cause pressure variances. These changes in pressure can result in imbalances in the flow of gas, which can lead to problems

like gas crossover, which is the blending of hydrogen and oxygen inside the fuel cell, reducing its efficiency and perhaps damaging the membrane (Gerard et al., 2010).

Not only does the pressure inside the cell need to be carefully managed, but the pressure throughout the entire system as well. Increased reactant concentration can be achieved by running the fuel cell at greater pressures, which will enhance reaction rates and overall efficiency. Higher pressures, however, can hasten the deterioration of the catalyst and membrane materials and thus raise the possibility of gas crossover. On the other hand, while operating at lower pressures can lessen the chance of degradation and crossover, it may also result in decreased efficiency and power production. One of the main challenges in the design and operation of PEMFC systems is achieving the ideal balance between pressure, gas distribution, and overall performance.

The dynamic operating circumstances of PEMFCs add another layer of complexity to the problems associated with hydrogen and oxygen flow management. In practical applications, like automobiles, power consumption can fluctuate greatly over time, causing changes in hydrogen and oxygen supply and consumption. These variances can result in momentary imbalances in the distribution of gases, which can create problems including pressure fluctuations, unequal current distribution, and brief starving of hydrogen or oxygen. Advanced control algorithms that may modify reactant flow in real-time to maintain optimal performances under variable conditions are needed to address these dynamic issues (Liu et al., 2020).

Researchers are looking into a number of approaches to deal with the problems associated with managing oxygen and hydrogen flow. These include the use of novel GDL materials that enhance gas permeability and water management, as well as the development of more

sophisticated flow field designs that maximize gas distribution while minimizing pressure drop and water accumulation. Furthermore, cutting-edge control systems are being created to continuously monitor and modify reactant flow, guaranteeing that oxygen and hydrogen are supplied at the best rate possible under the specified operating circumstances.

All things considered, controlling the flow of hydrogen and oxygen within a PEMFC is a difficult task with many facets that calls for careful consideration of a number of interconnected elements, such as pressure control, GDL characteristics, flow field design, and real-time system monitoring. Optimizing PEMFC system performance, efficiency, and durability requires addressing these issues.

2.2.2 Impact of flooding and pressure variations on performance

Ijaodola et al., (2019) demonstrate the Flooding and pressure changes are two of the biggest issues affecting PEMFC performance and dependability. These problems, which have a direct bearing on how the fuel cell distributes water and gas, can cause major performance losses, hasten the deterioration of cell components, and lower system efficiency all around.

Flooding happens when too much water builds up inside the fuel cell, especially in the flow field channels, catalyst layers, and gas diffusion layers (GDLs). The build up of water can obstruct the paths used by reactant gases, including oxygen and hydrogen, to reach the active sites on the catalyst layers. As a result, the cell's total power production is reduced. On the cathode side of the fuel cell, where water is created as a by product of the electrochemical process between oxygen, protons, and electrons, flooding is mostly an issue.

Water naturally forms in the fuel cell as a result of the electrochemical reactions that produce energy. However, a number of variables, such as the operating temperature, humidity, pressure, and the layout of the flow field and GDL, affect how much water is created and how

well the cell is able to manage this water. Flooding may happen if the cell is unable to evacuate water effectively, which could cause a number of performance problems. Reduced availability of active catalyst sites for electrochemical processes is one of the main effects of floods. Water can cover catalyst particles in the catalyst layer, obstructing reactant gasses from reaching these sites and lowering the rate of reaction overall. The cell can't use its full capacity for energy conversion as a result, which lowers power production and efficiency (Han et al., 2008).

Flooding can decrease the amount of active catalyst sites available while simultaneously raising the fuel cell's internal resistance. Water build up in the flow field channels and GDLs can physically obstruct the flow of reactant gases, lowering the cell's pressure drop and making it more challenging for oxygen and hydrogen to reach the catalyst layers. Higher energy losses within the cell and decreased overall efficiency may result from this increased resistance (Li et al., 2018).

Over time, fuel cell component deterioration can also be caused by flooding. Excessive amounts of water can cause liquid water films to form on the membrane, which can lower its proton conductivity and raise the possibility of membrane breakdown. Dafalla et al., (2018) demonstrate the build up of water can result in mechanical strains that induce cracking, delimitation, and other physical damage inside the GDL and catalyst layers. These problems have the potential to shorten the fuel cell's lifespan and raise the frequency of component replacement and maintenance over time.

Numerous tactics have been developed to lessen the effects of flooding. These include the adoption of cutting-edge flow field designs that encourage efficient water evacuation and the creation of more hydrophobic GDLs that reject water and stop it from building up. In order to

reduce the chance of flooding, the fuel cell's operational parameters, including temperature, humidity, and pressure, can also be precisely regulated. One way to lessen the chance of flooding is to run the fuel cell at a slightly higher temperature, which will accelerate the pace at which water evaporates.

The fuel cell's performance and dependability are also significantly influenced by pressure changes inside of it. Changes in the reactant gas supply, modifications to the flow field design, and variations in the operating environment can all cause these variations. Pressure fluctuations can result in an unbalanced distribution of hydrogen and oxygen inside the cell, which can lead to problems like gas crossover, which lowers the cell's overall efficiency by allowing hydrogen and oxygen to mix inside the membrane (Omrani et al., 2019).

The fuel cell's internal water management system is one of the main effects of pressure changes. Water's phase behaviour, including its transport via the flow field channels and the GDL, is influenced by the pressure inside the cell. Flooding could result from water evaporating inefficiently if the pressure is too low. On the other hand, excessive pressure can cause water to condense too quickly, which can also result in flooding and poor performance.

Changes in pressure can also impact the fuel cell's overall efficiency by modifying the electrochemical processes' reaction rates. Higher pressures typically result in higher reactant gas concentrations, which boost power output and reaction rates. Advanced control systems are commonly utilized to monitor and regulate the fuel cell's internal pressure in real-time, addressing the issues posed by pressure changes. By optimizing the pressure according to the existing working conditions, these systems make sure that it is within the ideal range for durability and performance. Furthermore, it is possible to improve the design of the GDL and

flow field to reduce pressure drops and guarantee that the reactant gases are distributed uniformly across the cell.

One important factor influencing PEMFC performance is the interaction between floods and pressure changes. Reaction rates, gas distribution, and overall efficiency must all be balanced, and this can only be achieved through efficient water management and pressure control. Technological developments in materials science, system architecture, and control schemes are still essential for overcoming these obstacles and enhancing PEMFC performance and dependability.

2.3 Control techniques for PEMFCs operation

Proton Exchange Membrane Fuel Cells (PEMFCs) depend heavily on regulation for optimal performance, lifetime, and efficiency. Robust and adaptive control mechanisms are necessary to manage the numerous operating issues, including temperature regulation, water management, pressure control, and the management of hydrogen and oxygen flow. This is because PEMFC systems are dynamic and have inherent complexities. Traditional Proportional-Integral-Derivative (PID) control is one of the several control methods that are accessible, and it has been extensively utilized in PEMFC applications. Nonetheless, the investigation of more sophisticated control techniques, such as fractional-order control, has been prompted by PID control's shortcomings in managing the nonlinearities and dynamic behaviour of PEMFCs.

2.3.1 Overview of traditional PID control in PEMFC

PID control, which stands for proportional-integral-derivative control, is a widely utilized control strategy in industrial applications because of its versatility, resilience, and efficiency in a variety of systems. The error, or discrepancy between the system's measured output and

the intended set point, is the basis on which the PID controller continuously modifies the control input. Three terms are added together to calculate the control input: the derivative term (D), which is proportional to the error's rate of change; the integral term (I), which is proportional to the error's cumulative error over time; and the proportional term (P), which is proportional to the error's current error.

PID controllers have been widely utilized in PEMFCs to control a variety of parameters, including temperature, pressure, current density, and the rates at which hydrogen and oxygen flow. In PEMFC applications, the major objective of the PID controller is to keep these parameters within ideal bounds, guaranteeing steady and effective fuel cell operation. For instance, the PID controller modifies the flow of gases to fit the demand based on the load circumstances when regulating the flow rates of hydrogen and oxygen, preventing problems like starvation or flooding. Similar to this, in pressure control, the PID controller minimizes the chance of gas crossing and membrane deterioration while maximizing the electrochemical reactions by regulating the reactant gas pressure (Božić et al., 2020).

There are various reasons why PID control is so prevalent in PEMFC applications. First, PID controllers can be used for real-time control in embedded systems since they are easy to implement and don't need a lot of processing power. Secondly, PID controllers exhibit robustness and may deliver excellent performance even when confronted with external disruptions and model uncertainty. Third, to achieve flexibility in varying operating conditions, the PID parameters (proportional gain, integral time, and derivative time) can be manually adjusted or adjusted using recognized techniques such the Cohen-Coon method, Ziegler-Nichols method (Copeland 2008), or manual tuning.

Traditional PID control, albeit widely used, has a few drawbacks when it comes to PEMFC systems. The nonlinear and time-varying dynamics of PEMFCs present a major difficulty. PEMFCs display intricate behaviour as a result of various circumstances, including aging effects, temperature fluctuations, changes in load conditions, and problems with water management. PID control's linear nature makes it challenging to manage these nonlinearities, which results in less efficient and less-than-ideal performance (Sung et al., 1996).

PID control's incapacity to manage multiple-input, multiple-output (MIMO) systems well is another drawback in PEMFC applications. Because PEMFCs are intrinsically MIMO systems, achieving optimal performance requires simultaneous control of several parameters (such as flow rates, pressure, and temperature). It can be difficult to adapt traditional PID controllers to MIMO systems because they are primarily made for single-input, single-output (SISO) systems. This can result in problems including instability and poor dynamic response, as well as control loop interaction.

PID controllers are also susceptible to changes in parameters and outside disruptions. PID controller performance in PEMFC systems can be greatly impacted by variables including load variations, temperature swings, and reactant supply changes. Although these problems can be resolved with strategies like gain scheduling or adaptive control, these approaches complicate the control system and might not be enough to manage the entire range of operating situations present in PEMFC systems.

Researchers have looked into more sophisticated control techniques, such as model-based control, adaptive control, and nonlinear control, to overcome these constraints. Fractional-order control, which expands the conventional PID controller into a more universal framework that can better capture the dynamics of complex systems like PEMFCs, is one of

the most promising methods, though. Basic diagram of PID controller with PEMFC shown in the figure 2.14.

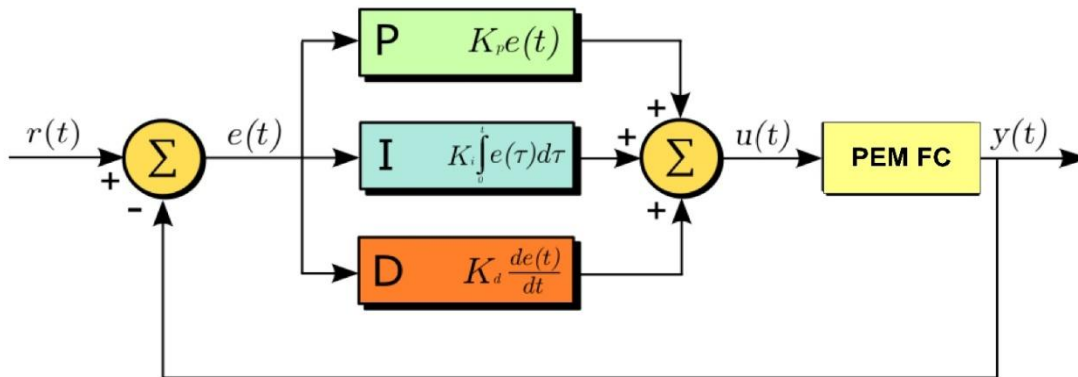


Figure 2.14 Basic PID controller

2.3.2 Introduction to Fractional-Order Control

An advanced control technique known as fractional-order control applies the idea of integer-order PID control to fractional calculus. The sequence of differentiation and integration in fractional calculus can take non-integer values, enabling a more accurate and versatile depiction of the dynamics of the system (Xue 2017). In order to handle the nonlinearities and complicated dynamics of systems like PEMFCs, fractional-order controllers, such as the Fractional-Order Proportional-Integral-Derivative (FOPID) controller, have been proposed as a way to get around the limits of classic PID control.

The capacity of fractional-order control to more effectively simulate the dynamics of real-world systems—many of which exhibit behaviour that integer-order models are unable to adequately capture—is one of its main advantages. Numerous elements, including as mass transport phenomena, aging processes, heat impacts, and electrochemical reactions, affect the dynamics of PEMFC systems. These variables frequently produce complicated, time-varying, non-linear behaviour that is challenging to capture with conventional integer-order models

and controllers. However, by include memory effects and capturing the long-term interdependence typical of such systems, fractional-order models can offer a more realistic picture of these dynamics.

Better robustness and performance in the face of model uncertainty and outside disturbances are two more benefits of fractional-order control. The fractional orders λ and μ give the controller extra degrees of freedom to fine-tune the control response and strike the ideal balance between performance, robustness, and stability. For instance, the controller can be made more responsive to low-frequency disturbances—which are common in PEMFC systems—while preserving stability and lowering overshoot by modifying the fractional orders.

Additionally, fractional-order control has advantages in terms of flexibility and adaptability. The capacity to modify the control response based on real-time data is essential in PEMFC applications, where operating conditions might change dramatically over time. By dynamically varying the fractional orders λ and μ , fractional-order controllers can be tailored to respond to changing circumstances and maintain control efficacy in a variety of operating settings (Chen et al., 2009).

2.3.3 Fractional calculus:

There are various definitions of fractional derivatives. Perhaps the most recognised is the Grunwald-Letnikov definition. The continuous function $f(t)$ of p^{th} order fractional derivative can be found using following derivation:

$${}_a D_t^p f(t) = \lim_{h \rightarrow 0} h^{-p} \sum_{j=0}^{\lceil \frac{t-p}{h} \rceil} (-1)^j \binom{p}{j} f(t-jh) = \frac{\partial^p f(t)}{\partial t^p}$$

Where $\left[\frac{t-p}{h} \right]$ is truncation; $\binom{p}{j}$ is binomial coefficient

$\binom{p}{0} = 1$, $\binom{p}{j} = \frac{p(p-1)\dots(p-j+1)}{j!}$, it can be replaced by gamma function

$$\binom{p}{j} = \frac{\Gamma(p+1)}{j!\Gamma(p-j+1)}$$

The general calculus operator (including fractional order and integral order is defined as

$${}_a D_t^\alpha = \left\{ \begin{array}{l} \frac{\partial^\alpha}{\partial t^\alpha} \dots \Re(\alpha) > 0 \\ 1 \dots \Re(\alpha) = 0 \\ \int_a^t (d\tau)^{-\alpha} \dots \Re(\alpha) < 0 \end{array} \right\}$$

The application of fractional-order control in PEMFC systems comes with a number of difficulties despite its benefits. The FOPID controller's design and tuning provide one of the main obstacles. Due to the additional degrees of freedom that the fractional orders provide, the tuning of FOPID controllers is more complicated than that of typical PID controllers, where well-established tuning techniques like the Ziegler-Nichols approach are used. A number of techniques, including optimization-based strategies like genetic algorithms (GA), particle swarm optimization (PSO), and grey wolf optimization (GWO), have been put forth for fine-tuning FOPID controllers. With the use of these techniques, one can find the ideal combination of controller parameters—including fractional orders—that minimizes a certain performance metric, like the integral of the absolute error (IAE).

The computational complexity of the fractional-order operators presents another difficulty in the use of fractional-order control. Specialized numerical techniques must be used to

calculate fractional derivatives and integrals; these techniques can be computationally demanding and cause delays in the control system. This is especially important for real-time applications where accuracy and speed of reaction are crucial, like PEMFC control. To overcome this difficulty, a number of approximation strategies have been created that preserve the precision of the control response while lessening the computational load of fractional-order operators.

Fractional-order control has demonstrated significant potential in enhancing the reliability and performance of PEMFC systems despite these obstacles. Numerous studies have shown how well FOPID controllers work in controlling important variables under a variety of operating circumstances, including temperature, pressure, and the rates at which hydrogen and oxygen flow. Specifically, it has been demonstrated that FOPID controllers outperform conventional PID controls in terms of overshoot, settling time, and robustness to disturbances (Bingi et al., 2020)

2.3.4 Comparison of Fractional-Order and Integer-Order Controllers

In the context of PEMFC control, a comparison between fractional-order controllers (like FOPID) and conventional integer-order controllers (like PID) highlights a number of significant distinctions and benefits of the fractional-order approach.

The degree of reaction flexibility and adaptability of fractional-order and integer-order controllers is one of their main distinctions. Fixed proportional, integral, and derivative gains dictate the control response in conventional PID controllers. Although these improvements can be tuned to produce the required performance, the controller's inflexible structure prevents it from responding to modifications in the dynamics of the system or in the operating environment. However, by utilizing the fractional orders λ and μ , fractional-order

controllers offer more degrees of freedom, enabling more accurate adjustment and modification of the control response. (Bingi et al., 2020)

The capacity of fractional-order and integer-order controllers to manage intricate, nonlinear dynamics is another important distinction. As was previously indicated, the interaction of temperature effects, mass transport processes, and electrochemical reactions results in a wide range of dynamic behaviour in PEMFC systems. Due to their linear design, traditional PID controllers frequently struggle to appropriately represent these intricate dynamics, which results in less than ideal performance and decreased efficiency. In contrast, fractional-order controllers can offer a more realistic depiction of the system dynamics by taking long-term dependencies and memory effects into account. Better control over the PEMFC system is made possible by this, leading to increased effectiveness and performance.

Fractional-order controllers have advantages over conventional PID controllers in terms of durability and stability. The fractional orders provide the controller more degrees of freedom, enabling more accurate tuning to strike the right balance between performance, robustness, and stability. Fractional-order controllers, for instance, can be adjusted to reduce overshoot and preserve stability while offering improved rejection of low-frequency disturbances, which are frequent in PEMFC systems. As a result, the control system becomes more resilient and is able to continue operating at peak efficiency even when there are outside disruptions and model uncertainties (Soukkou et al., 2016).

Numerous studies have shown the effectiveness of fractional-order controllers in PEMFC applications. For instance, studies have demonstrated that FOPID controllers outperform conventional PID controllers in terms of overshoot, settling time, and robustness to disturbances. Specifically, it has been demonstrated that FOPID controllers in PEMFC

systems offer superior control over temperature, pressure, and flow rates of hydrogen and oxygen, leading to increased longevity and efficiency.

Fractional-order controller implementation in PEMFC systems is not without difficulties, despite these benefits. As previously indicated, because the fractional orders provide additional degrees of freedom, FOPID controllers require more intricate design and tuning than typical PID controllers. This complexity might make tuning more difficult and time-consuming when using optimization-based methods like particle swarm optimisation or genetic algorithms.

Moreover, real-time applications may encounter difficulties due to the fractional-order operators' computational complexity. Specialized numerical techniques must be used to calculate fractional derivatives and integrals; these techniques can be computationally demanding and cause delays in the control system. This is especially important for PEMFC control, where quick decision-making is essential. To overcome this difficulty, a number of approximation strategies have been created that preserve the precision of the control response while lessening the computational load of fractional-order operators. Table 2.1 shows the key comparison points.

2.4 Optimization algorithms for controller design

For Proton Exchange Membrane Fuel Cells (PEMFCs) to operate as efficiently and long as possible, control mechanisms must be optimized. Because PEMFC systems are complicated and have variable operating conditions, nonlinear dynamics, and sensitivity to shocks, strong optimization algorithms are needed for the design of efficient controllers. To tackle these issues, a number of optimization strategies have been created and improved over time, with some of the more well-known approaches being Genetic Algorithms (GA), Particle Swarm

Optimization (PSO), and Grey Wolf Optimization (GWO). Every one of these algorithms has its own benefits and has been effectively used in the PEMFC controller design context. In-depth examination of various optimization methods and a comparison of their suitability and efficacy within the framework of PEMFC control are provided in this section.

Table 2.1 Comparison between traditional and fractional order controller (Sierociuk et al., 2013)

Aspect	Traditional PID Control	Fractional-Order Control (FOPID)
Basic Concept	Uses integer-order proportional, integral, and derivative actions (P, I, D).	Uses non-integer (fractional) order proportional, integral, and derivative actions (P, I, D with fractional orders λ , μ).
Flexibility	Limited flexibility with fixed P, I, and D terms.	High flexibility due to adjustable fractional orders (λ , μ) allowing for fine-tuning of the control response.
Adaptability to System Changes	Limited adaptability; requires manual retuning for significant changes in system dynamics.	High adaptability; fractional orders can be dynamically adjusted for changing conditions.
Handling of Nonlinear Dynamics	Less effective in handling complex, nonlinear dynamics.	More effective in capturing and controlling nonlinear dynamics due to fractional-order modeling.
Robustness	Generally robust, but performance can degrade with model uncertainties and disturbances.	Enhanced robustness with better disturbance rejection and stability, especially in low-frequency disturbances.
Response to Disturbances	Can be less effective in rejecting low-frequency disturbances; more prone to overshoot.	Better disturbance rejection with lower overshoot and faster settling time.

2.4.1 Genetic Algorithms (GA)

One of the most popular optimization methods in control system design is genetic algorithms, especially for intricate, nonlinear systems such as PEMFCs. Motivated by natural selection, GAs use a population-based search mechanism in which possible answers, or people, develop over a series of generations. Beginning with a population of potential solutions that are randomly produced, the algorithm assesses each one according to a fitness function that gauges how well it performs in relation to the goal function (Krishnakumar et al., 1992). The goal of PEMFC control may be to maximize stability and efficiency or to reduce overshoot, settling time, and steady-state error.

Three main players are involved in GA evolution: crossover, mutation, and selection. To pass on their genes, or their qualities, to the following generation, selection entails selecting the fit individuals. Similar to biological reproduction, crossover unites two individuals to produce progeny that may have superior traits. By introducing random differences in the progeny, mutations help preserve genetic variety within the population and delay the early convergence of the population toward less-than-ideal solutions.

GAs has been very useful in PEMFC controller design for optimizing integral square error (ISE), Integral absolute error (IAE), integral time square error (ITSE). GA-based optimization can greatly enhance the performance of the fractional-order PID (FOPID) controller, which is a variation of the ordinary PID that incorporates fractional calculus (Jaiswal et al., 2020). To strike a compromise between robustness, stability, and performance, GA can be used to adjust the fractional orders in addition to the conventional PID settings. For instance, GA can optimize the controller performance to maintain peak overshoot, delay time, rise time settling time with in desire level where PEMFCs are subject to fluctuating load demands and environmental conditions. Figure 2.15 shows the GA approach for PEMFC.

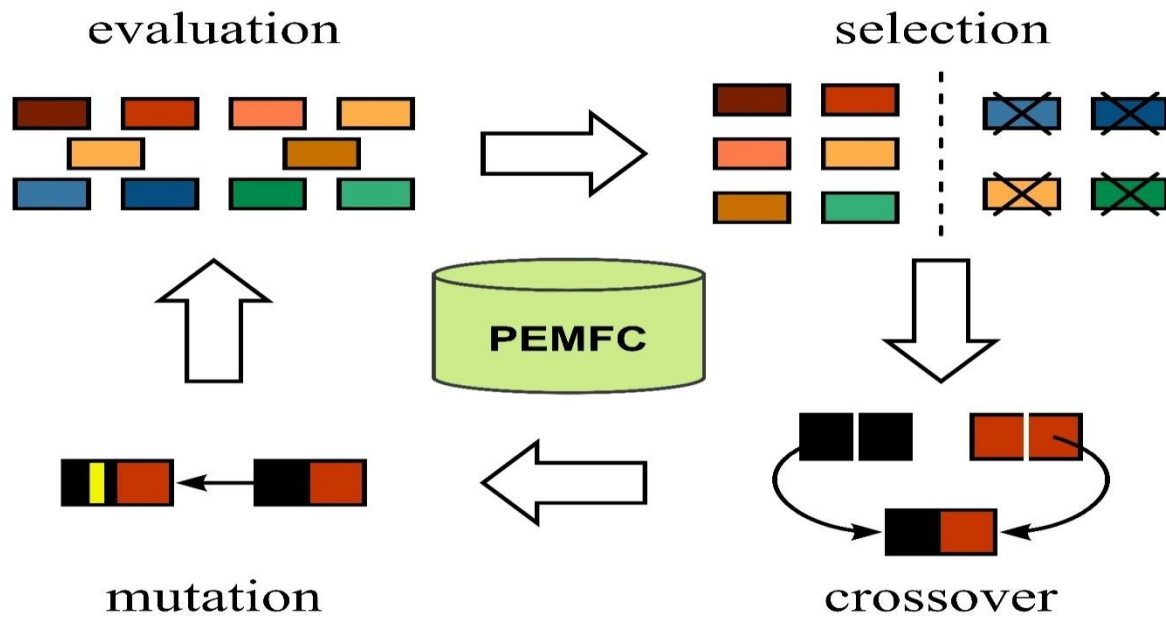


Figure 2.15 GA based approach for PEMFC

Because of their flexibility, GAs can be used in PEMFC systems, where the control objectives are subject to dynamic changes. The primary issue with GAs, meanwhile, is their computational expense, especially when working with big populations or intricate fitness functions. Furthermore, GAs has the potential to prematurely converge to local optima, particularly in cases when population diversity is low. Despite these difficulties, GAs' flexibility and resilience make them an effective tool for PEMFC controller optimization.

2.4.2 Particle Swarm Optimization (PSO)

Another well-liked optimization approach is Particle Swarm Optimization (PSO), which is renowned for being both straightforward and effective. The social behaviour of fish schools and flocks of birds serves as an inspiration for PSO. In these situations, each particle (possible solution) in the swarm navigates the search space by modifying its position in response to both its own and its neighbour's experiences. PSO, in contrast to GAs, finds the best solution by utilizing the ideas of velocity and position updates rather than crossover and mutation operators.

Every particle in PSO has a velocity vector that it uses to calculate how far it can travel in a given direction and how much. The particles update their positions and velocities repeatedly depending on two key factors: the global best, which is the best solution found by the entire swarm, and the personal best, which is the best solution found by the particle alone. Due to these two influences, PSO is able to strike a balance between exploitation (improving existing good answers) and exploration (exploring new regions of the search space).

PSO has proven to be an excellent tool for optimizing PEMFC controllers, especially when it comes to fine-tuning the settings of FOPID controllers. The technique is well-suited for real-time control applications where computational economy is crucial because of its rapid convergence to a near-optimal solution. To maintain optimal performance, PSO can dynamically alter the controller parameters in PEMFC systems, for instance, where the load circumstances may vary quickly (Anil et al., 2021). Figure 2.16, shows the general approach for the same.

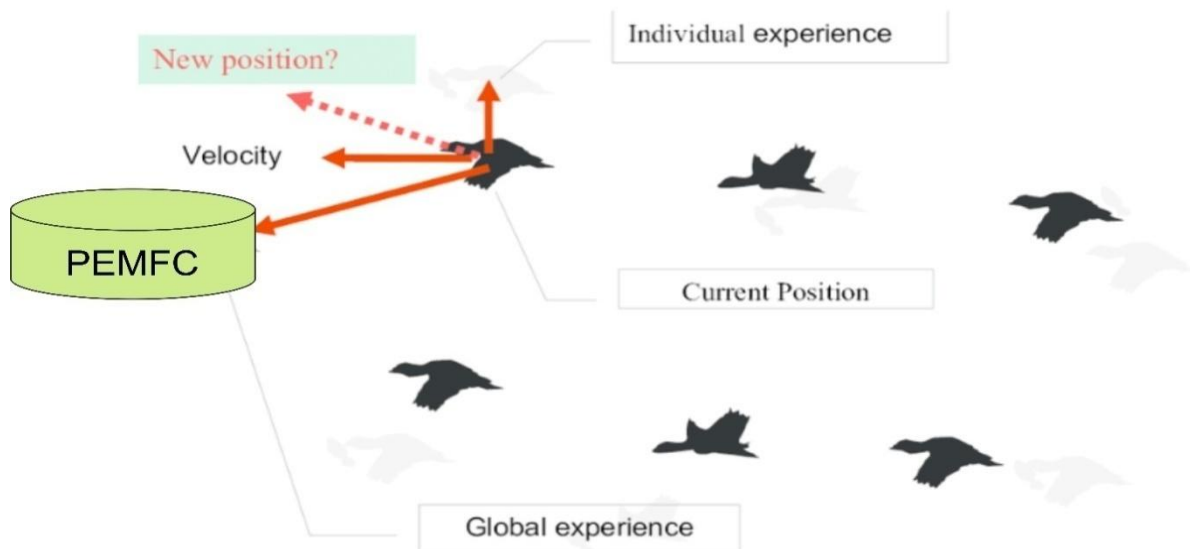


Figure 2.16 PSO approach for PEMFC

PSO's relative simplicity and lower computing cost are two important advantages over GAs. PSO is quicker and simpler to execute since it doesn't involve intricate procedures like crossover and mutation. Furthermore, PSO converges faster than GAs, particularly in continuous, smooth search spaces. PSO, however, may find it difficult to navigate multimodal or extremely complicated fitness landscapes because it may become stuck in local optima. To counteract this, PSO variants like Adaptive PSO and Hybrid PSO have been created to improve the algorithm's performance in difficult optimization tasks.

2.4.3 Grey wolf optimization (GWO)

Inspired by the social hierarchy and hunting behaviour of grey wolves, Grey Wolf Optimization (GWO) is a relatively modern algorithm in the family of nature-inspired optimization algorithms. The hunting strategy and leadership structure of grey wolves in the wild—in which the omega wolves pursue after the alpha, beta, and delta wolves—are replicated in GWO. The alpha wolf indicates the optimal answer, beta and delta wolves direct the search, and omega wolves scout the search space. This hierarchy is utilized to direct the search process.

The three key stages of the optimization process in GWO are encircling, hunting, and attacking the target. Based on the locations of the alpha, beta, and delta wolves, the wolves modify their positions in relation to the prey (ideal solution) during the encircling phase. The wolves converge on the prey during the hunting phase, but during the attacking phase, they narrow the search area in order to focus on fine-tuning the strategy as they approach the target (Faris et al., 2018)

GWO has demonstrated significant potential in PEMFC controller optimization because of its skill at skilfully balancing exploration and exploitation. A more structured search process is

made possible by GWO's hierarchical structure, in which the best solutions point the remainder of the population in the direction of the best answer. In PEMFC systems, where the control parameters must be precisely adjusted to manage the complicated dynamics and fluctuating operating circumstances, this can be especially helpful.

GWO has several advantages over GA and PSO, one of which is its capacity to prevent local optima and accomplish a more comprehensive search of the solution space. Premature convergence is less likely when the wolves' placements are dynamically adjusted depending on the best solutions discovered thus far, preserving population variety. GWO is well suited for real-time optimization in PEMFC control applications due to its comparatively low computational complexity.

Like any optimization algorithm, GWO is not without its difficulties. The convergence factor and the number of wolves are two examples of algorithm parameters that can have an impact on GWO's performance. To get the greatest performance in PEMFC applications, these parameters must be fine-tuned. Moreover, even though GWO typically works well in most situations, it might need more hybridization with other algorithms or improvements to properly address highly complicated or high-dimensional optimization issues.

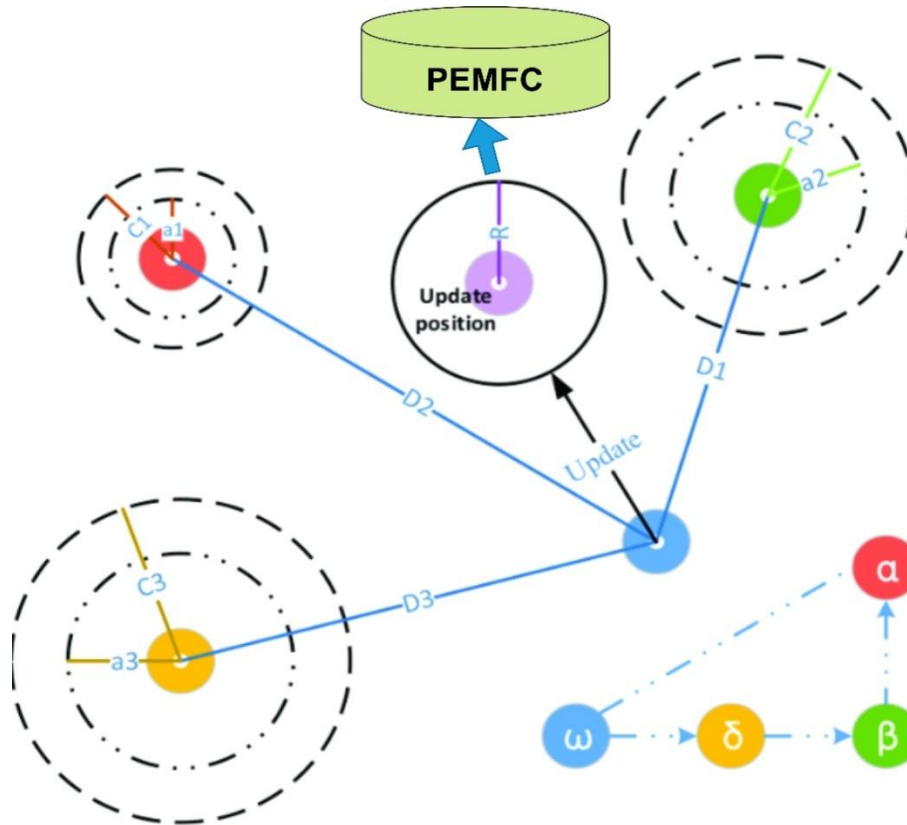


Figure 2.17 GWO basic principle for PEMFC

To get the highest performance in PEMFC controller design, hybrid techniques that combine the advantages of several optimization algorithms are frequently used in practice. A hybrid GA-PSO or GWO-PSO algorithm, for instance, can combine the quick convergence of one algorithm with the global search capabilities of another to produce a more reliable and effective optimization result (Silaa et al., 2022). Likewise, performance can be further improved by adaptive algorithms that dynamically modify their parameters in response to the optimization process, especially in uncertain and dynamic situations such as PEMFC systems.

2.4.4 Comparison of different optimization techniques

In summary on the literature review, it can be stated that the PEMFC controller optimization is a crucial endeavour that necessitates carefully taking into account the underlying system dynamics, control goals, and available computational resources. Particle Swarm Optimization, Grey Wolf Optimization, and Genetic Algorithms are all effective methods for design and tweaking, but they each have their own special benefits.

Table 2.2 Comparison of optimization methods (Yarat et al., 2021)

Criteria	Genetic Algorithm (GA)	Particle Swarm Optimization (PSO)	Grey Wolf Optimization (GWO)
Inspiration	Natural selection and genetics	Social behaviour of birds or fish	Social hierarchy and hunting behaviour of grey wolves
Search Mechanism	Population-based with selection, crossover, and mutation	Population-based with velocity and position updates	Population-based with encircling, hunting, and attacking phases
Handling of Local Optima	Prone to premature convergence; diversity maintained through mutation	Can get trapped in local optima, especially in complex fitness landscapes	Effective at avoiding local optima due to the dynamic adjustment of wolf positions
Computational Complexity	Moderate to high, depending on population size and number of generations	Generally low; computationally efficient	Moderate; lower than GA but higher than PSO

Convergence Speed	Can be slow due to the need to evolve over many generations	Generally faster; efficient in smooth search spaces	Balanced; convergence depends on the number of wolves and the dynamics of hierarchy
Implementation Complexity	Moderate to high; requires handling of crossover, mutation, and selection operations	Low; simple to implement with basic velocity and position updates	Moderate; involves more steps but still straightforward

2.5 Recent advanced trends in PEMFC control

The ability of proton exchange membrane fuel cells (PEMFCs) to convert hydrogen and oxygen into electricity with the sole by-product being water makes them essential in the search for clean energy sources. Even with its promise, PEMFCs are still quite difficult to operate at peak efficiency, especially when it comes to controlling the flow of hydrogen and oxygen, controlling pressure, and managing the fuel cell system as a whole. PEMFC control approaches have advanced significantly in recent years due to the requirement to improve durability, efficiency, and dependability under a range of operating circumstances. This section highlights the research gaps that still need to be filled and summarizes the latest developments in PEMFC control.

2.5.1 Summary of recent research and advancements in PEMFC control

The development of increasingly complex and responsive control systems to handle the dynamic and nonlinear behaviour of fuel cells has been the main focus of recent advances in PEMFC control. The transition from conventional control strategies, such as PID (Proportional-Integral-Derivative) control, to more sophisticated approaches, like fractional-order control

and intelligent optimization algorithms, is one of the most important developments in this discipline.

Fractional-Order Control: Because it can better simulate the dynamics of PEMFCs, fractional-order control has become a viable strategy. Fractional-order controllers, as opposed to conventional integer-order controllers, are better able to capture the intricate, non-linear properties of PEMFCs, improving overall performance, stability, and resilience. Fractional-order controllers have been shown in recent research to be efficient at lowering overshoot, improving response times, and preserving stability under a range of loads and disturbances. It has been demonstrated, for example, that fractional-order $PI^\lambda D^\mu$ (FOPID) controllers perform better than conventional PID controllers, especially when it comes to lowering system overshoot and enhancing stability. This has been ascribed to the fractional orders' extra degrees of freedom, which enable more accurate controller parameter tweaking.

Optimization Algorithms: Another important development in PEMFC control is the combination of fractional-order control techniques with intelligent optimization algorithms, like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO). The controller parameters have been optimized with the help of these algorithms, guaranteeing the PEMFC's effective operation in a variety of scenarios. GWO, for instance, has been acknowledged for its exceptional performance in avoiding local minima, offering improved global search capabilities, and optimizing FOPID controllers—all of which are frequent difficulties in intricate, nonlinear systems such as PEMFCs. Fractional-order controllers and these algorithms have significantly increased the efficiency and dependability of PEMFC systems, increasing their viability for real-world applications.

Model Predictive Control (MPC): As an enhanced control technique for PEMFCs, Model Predictive Control (MPC) has also gained popularity recently. MPC forecasts future behaviour and optimizes control actions based on it using a model of the PEMFC system. This method works especially well for controlling the multivariable nature of PEMFCs, where it's important to properly coordinate the interactions between several control inputs, such as temperature, oxygen flow, and hydrogen flow. Wang et al., (2021) demonstrated that MPC can greatly increase PEMFC stability and efficiency, especially when managing fluctuations and changing operating conditions. MPC can proactively modify control inputs by forecasting future states of the system, which lowers the chance of performance degradation brought on by unanticipated disruptions.

Artificial Intelligence and Machine Learning: Another area that has seen substantial breakthroughs is the application of AI and ML in PEMFC control. Adaptive control algorithms that can learn from the PEMFC's operating data and modify control parameters in real-time have been developed using AI and ML approaches. This is especially helpful in managing the inherent unpredictability and uncertainties in PEMFC operations, such as variations in fuel quality, temperature swings, and load demand (Sharma et al., 2024). Recent research on PEMFC control has looked at the application of neural networks, fuzzy logic, and reinforcement learning. These approaches have the potential to increase system performance, lower energy consumption, and lengthen the fuel cell stack's lifespan.

Table 2.3 An overview of PEMFC fuel control schemes

Generic Control Technique	Control Strategy	Implementation of control Strategy	Performance	References
Classical feedback and feed forward control using proportional, integrative and derivative control (PID)	Single input single output control system (SISO)	Feedback PID control of current through stoichiometry manipulation of either hydrogen or air	quicker reaction and a lower chance of fuel shortage if the hydrogen stoichiometry is changed	Filo et al., (2022)
	Decentralized multi input multi output control (MIMO)	Control of the air-hydrogen pressure differential by manipulation of hydrogen stoichiometry and feedback control of voltage through manipulation of air stoichiometry.	The best controllability index for pairs of control-manipulated variables	Mohanty et al., (2021)
Adaptive control	Sliding mode control (SMC)	Sliding mode (feedback) control (SMC) of oxygen stoichiometry and feed-forward control of output current	Maintaining oxygen stoichiometry prevents oxygen deprivation.	Utkin et al., (2013)
	Self-tuning PID control (STPID)	In order to adjust to changing non-linear dynamics, PID controller constants are continuously returned.	Maintaining oxygen stoichiometry prevents oxygen deprivation.	Lin et al., (2000)
	Robust adaptive	Adaptive air stoichiometry control,	Adaptive regulation of	

	control (RAC)	whose parameters are determined using the assignment of closed-loop poles and the closed-loop least square parameter identification algorithm.	oxygen stoichiometry prevents oxygen starvation.	Lavretsky et al., (2012)
Model predictive control (MPC)	Constrained feed-forward model predictive control (CMPC)	By lowering the error between the actual and expected output current, the PEMFC's non-linear model updates the control action of the air flow rate for feed-forward control of current demand.	Limiting oxygen stoichiometry above starvation prevents oxygen deprivation.	Koerber et al., (2013)
	Explicit constrained, linearized model predictive (CLMPC)	By lowering the error between the actual and anticipated output current, the linearized model of PEMFC is utilised to update the control action of air flow rate for feed forward control of current demand for maximum efficiency and starving control or feedback voltage tracking.	Limiting oxygen stoichiometry above starvation prevents oxygen deprivation.	Hessemet al., (2006)
Artificial neural network control	Neural optimal control (NOC)	Using a parametric cerebellar model articulation controller (PCMAC) network,	Better results than traditional PI control	Jemei et al., (2008)

(ANNC)		which has short-term memory trained online and long-term memory trained offline, current demand is controlled.		Gulcehre et al., (2018)
	Dynamic neural network control (DDNC)	Current demand can be controlled by adjusting the hydrogen flow rate and utilising a dynamic neural network (DNN), which is constantly learning.	Better results than traditional PI-only control	
Fuzzy logic control	Fuzzy logic control	Based on observations of system behaviour, input and output variables for air flow rate control are fuzzified into fuzzy sets, and output variables are then defuzzed to generate control action.	Compared to MPC-PID control, there is a substantially lower overshoot and a much smaller transient power decrease during the step shift of current demand.	Benchouia et al., (2015)
Artificial intelligence based control	Artificial intelligence based control	Data-based models for the performance attributes have been developed using machine learning techniques such as support vector machine regressors (SVR) and artificial neural networks (ANN).	minimises computation (no need for numerous epochs) without compromising precision.	Ashraf et al., (2022)

2.5.2 Gaps identified in current research

Even with the recent advancements in PEMFC optimization and control, there are still a number of issues that must be resolved in order to maximize the potential of this technology by using more efficient control strategies as identified below:

Scalability and Real-World Implementation: The scalability and real-world implementation of advanced control techniques in PEMFC systems represent one of the main research gaps at the moment. Although small-scale tests and simulations have demonstrated the immense potential of fractional-order controllers and optimization algorithms, there is still a limited use of these technologies in large-scale commercial PEMFC systems. This is because of a number of difficulties, including as the difficulty of putting these controllers into practice in real-time, the amount of computing power needed, and the requirement for sturdy hardware that can survive the severe operating conditions of PEMFCs. To provide easily integrated, scalable, and affordable solutions, more research is required.

Long-Term Stability and Durability: The long-term stability and durability of PEMFCs under sophisticated control systems represents a huge research gap that has to be filled. It is unclear how fractional-order controllers and optimization algorithms will affect the fuel cell stack's long-term stability and durability, even though they can temporarily increase PEMFC performance. For instance, constant parameter adjustments in response to changing circumstances may cause the fuel cell components to wear out more quickly and ultimately shorten their lifespan. To find ways to mitigate any detrimental effects and learn more about how these control measures affect PEMFC durability over the long term, more study is required.

Robustness and Uncertainty: PEMFC systems are robust and uncertain by nature, as their performance is affected by a variety of factors including fuel quality, humidity, temperature, and load demand. More reliable control methods are still required, even if recent developments in AI and ML have resulted in the creation of adaptive control systems that can manage some of this uncertainty. The majority of current research has concentrated on improving controller parameters under ideal circumstances; however PEMFCs are exposed to a variety of uncertainties and disturbances in real-world applications. It is still extremely difficult to develop control systems that can continue to provide optimal performance in these unpredictable circumstances.

Energy Management and Efficiency Optimization: More study is still needed in this area, even though much progress has been achieved in maximizing the performance of PEMFCs. This entails creating control plans that can optimize fuel resource utilization, reduce energy losses, and increase the overall efficiency of the energy conversion process. More study is specifically required to improve the efficiency and dependability of PEMFC integration with energy storage devices like super capacitors and batteries.

Multi-Objective Optimization: Lastly, research on PEMFC control techniques' multi-objective optimization is lacking. Real-world PEMFC systems necessitate the simultaneous optimization of many objectives, such as efficiency, durability, cost, and environmental effect. Most researches have concentrated on optimizing a single objective, such as stability or efficiency. It is imperative to address the enormous problem of developing control strategies that can effectively balance these opposing aims and offer a holistic solution for PEMFC management. Based on the above study, the research objectives for this study have been identified and summarized in the section 2.5.3.

2.5.3 Research objectives

Section 2.5.3 summarises and identifies the research gap based on the literature review. The research objectives are then listed below:

- (i) Create a fractional order PEMFC plant from a standard integer order PEMFC plant and create a new fraction order controller for the fractional order plant.
- (ii) Design a higher order mathematical model of PEMFC system and developed a suitable PID and FOPID controller for that system.
- (iii) In order to provide a steady power supply across the load, design a dc-dc boost converter that will be integrated with PEMFC. To optimise the controller parameter, use many well-established metaheuristic optimisation algorithms, such as GA, PSO, and GWO.

CHAPTER 3

MATHEMATICAL

MODELLING AND

DESIGNING OF PEMFC

SYSTEM

PEMFCs, or proton exchange membrane fuel cells, have drawn a lot of interest as a potentially effective and clean energy source. However, achieving maximum efficiency and reliability is hampered by the complex and dynamic nature of PEMFC systems. Accurately modelling and controlling the dynamics of a PEMFC is essential to its operation, especially when dealing with changing operating circumstances and disturbances. This chapter explores the mathematical modelling of PEMFC control systems with a focus on the incorporation of sophisticated control techniques including optimization algorithms and fractional-order controllers.

3.1 Introduction

A fuel cell is an electrochemical-based device that converts chemical energy into usable electrical energy without emitting harmful by-products like carbon dioxide. Hydrogen and oxygen make up the major parts of the fuel cell, which react with each other to produce electricity and water as a by-product. Development in the field of electrical vehicles the demand and research on energy storage devices is increasing day-by-day. Compare to traditional battery storage researchers are very much interested in fuel cell because they are clean and green source of energy. The most common used fuel cell in the market is Proton Exchange Membrane Fuel Cell (PEMFC) which uses hydrogen as main fuel (Lü et al., 2018). Although PEMFC is the most popular fuel cell but it has certain disadvantages like its non-linear characteristics, multi-input multi-output (MIMO) based system, and the load variation is stochastic in nature. These disadvantages create issues in design the controller unit for different operations.

The PEMFC is the combination of physics, chemistry, hydrodynamics, and a part of thermodynamics. Due to this fuel cell own a very complex characteristics owing to complex mechanism related to dynamics coupling. For the real time implementation of PEMFC one

should include the dynamic fractional order behaviour for modelling the accurate system. As a result, dynamic features of fuel cell research have been a prominent focus in this sector in recent years, also getting a push from electrical vehicle segments. Sharma et al., (2023) establishes overall working dynamic model which includes gas supply model, voltage model and model of temperature dynamics. The overall model was validated by monitoring the results on the physical platform. Ferng et al., (2007) demonstrate three-dimensional PEMFC model and its performance regarding liquid water using the CFD software. Lin et al., (2006) reveal two-dimensional model coupled with gas and liquid water. Then the system was analysed in terms of current density. Most of the literature shows that the majority of work attempt to model the complex dynamics of PEMFC. But for the future prospective in electrical vehicle and other related application it is important to focus on control strategies of PEMFC dynamics. A very few academicians have also made contributions to this topic, which requires further development in light of its current market use.

Chen et al., (2017) proposed a linear ratio controller with the aim to control the oxygen supply flow rate. By implementing this control strategy, the team find that the PEMFC has better dynamic response while decreasing the solid temperature. A similar approach was described by Damour et al., (2015) in which non-linear based model predictive controller were designed using the distributive parameters of PEMFC. The researchers observe that the system durability and efficiency increased. In the present scenario, most of the voltage control strategies used in fuel cells are controlled using PID based controller, fuzzy based controller, ANN and some other intelligent controller. The most effective type controller claimed in most of the literature review is sliding model-based control due to having advantages like no overshoot, fast response, small computational time and real-time implementation (Omer et al., 2020). But the controller suffers from tracking error due to

frequent switching and variable control structure. In similar manner, Benchouia et al., (2015) establish fuzzy based controller. It was not possible to provide unified design criteria for PEMFC, making the fuzzy based controller quite sluggish. The Neural network-based controller helps to solve the problem of uncertainty and non-linearity, which are complex in nature and are to be solved by the traditional existing methods. However, the neural based controller needs to be trained every time if the operating environment and performance parameters are changed.

3.1.1 Basic Modelling equation related to PEMFC

To evaluate the transient characteristics of the nonlinear PEMFC air feed system, a mathematical model must be developed. The 9th order state based model for the control of output power of PEMFC is proposed by Silaa et al., (2020). It involves a very complex arithmetic operations and different equations that are immensely nonlinear in nature, so for controlling purposes, a 4th order influence viewing angles for the PEMFC scheme developed by Divi et al., (2019) was considered. By adhering to the presumptions, it was shown that the atmospheric feed structures could be highly separated through the whole fuel cell architecture while maintaining the PEMFC's dynamic related behaviour.

(a) The pressure in the anode delivery manifold is kept under good control and at the desired level.

(b) The physics related to model of the PEM fuel cell is described by the formulas that govern it stated below.

(c) The humidity and temperature at the PEMFC stack's introduction are almost constant. The partial pressures of nitrogen and oxygen are then calculated using the law of mass conservation, and the ideal gas law:

$$\frac{dp_{O_2}}{dt} = \frac{RT_{fc}}{V_{ca}M_{O_2}} \left(F_{O_2,cathode,in} - F_{O_2,cathode,out} - F_{O_2,reacted} \right) \quad (3.1)$$

$$\frac{dp_{N_2}}{dt} = \frac{RT_{fc}}{V_{ca}M_{N_2}} \left(F_{N_2,cathode,in} - F_{N_2,cathode,out} \right) \quad (3.2)$$

Within which V_{ca} is the cathode volume as lumped, R is the universal gases constant, T_{fc} is the stacked temperature of the fuel cell, and M_{O_2} and M_{N_2} are the mole fraction masses of the O_2 and N_2 gases, respectively. Where $F_{O_2,cathode,in}$ and $F_{N_2,cathode,in}$ are the oxygen and nitrogen inlet mass flow rates, respectively. Whereas $F_{O_2,cathode,out}$ and $F_{N_2,cathode,out}$ are the oxygen and the nitrogen outlet mass flow rates, respectively. The continuity equation for the compressor motor's angular speed is given by the equation:

$$\frac{d\omega_{cp}}{dt} = \frac{1}{J_c} (\phi_{cm} - \phi_{cp}) \quad (3.3)$$

Where J_c is motor inertia and ϕ_{cm}, ϕ_{cp} represents compressor motor and compressor load torque. The characteristics of supply heat exchanger air pressure are defined through the complex differential equation stated below.

$$\frac{dp_{sm}}{dt} = \frac{RT_{cp}}{M_a V_{sm}} \left(F_{cp} - k_{cathode,in} (P_{sm} - P_{ca}) \right) \quad (3.4)$$

Where V_{sm} the amount of the supply manifold is, T_{cp} is the ambient temperature exiting the compressor, and F_{cp} is the compressed airflow rate.

This thesis adopts Suh's (2006) assumptions like:

1) The anode-side pressure is effectively managed.

The anode dynamics are not modelled since the supply manifold pressure on the anode side is taken to be constant and at the intended value. For control, only cathode-side air feed is taken into account.

2) The humidity and temperature remain unchanged.

It is expected that the fuel cell stack's intake temperature and humidity remain constant. The consequences of water and heat management are disregarded.

3) Ignore the electrodynamics of compressor motors

The electrical dynamics of compressor motors, including armature inductance and current fluctuation, are disregarded. Only the dynamics of mechanical torque and inertia are included in the model.

4) Air Feed System Handled Separately

The PEMFC subsystems (humidifier, stack voltage model, water balance, etc.) are not modelled in conjunction with the air-feed subsystem (compressor + supply manifold + cathode). It is assumed that adequate oxygen delivery and, hence, steady stack performance can be achieved by regulating the cathode supply manifold pressure.

5) Neglecting Specific Dynamics and Losses

The transfer function model excludes the electrochemical kinetics of the PEMFC, water transport, and temperature impacts on membrane conductivity. The model ignores stack voltage and current–voltage (I – V) characteristics in favour of concentrating only on supply manifold pressure dynamics. The effects of gas compressibility and transient diffusion within electrodes are grouped together as empirical constants rather than being explicitly modelled.

3.1.2 Dynamic air feed model in its entirety

The constants are derived from the above connections, and the simulation model of both the air-based feedback system is stated in the streamlined representation shown below.

$$x = \begin{bmatrix} P_{O_2} & P_{N_2} & \omega_{cp} & P_{sm} \end{bmatrix}^T = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T \quad (3.5)$$

The PEM fuel cell's proper state governing equations are as follows:

$$\dot{x}_1 = (x_4 - x_1 - x_2 - c_2)c_1 - \frac{c_3 x_1 F_{ca,out}}{c_4 x_1 + c_5 x_2 + c_6} - c_7 I_{stack} \quad (3.6)$$

$$\dot{x}_2 = (x_4 - x_1 - x_2 - c_2)c_8 - \frac{c_3 x_2 F_{ca,out}}{c_4 x_1 + c_5 x_2 + c_6} \quad (3.7)$$

$$\dot{x}_3 = -c_9 x_3 - \frac{c_{10}}{x_3} \left[\left(\frac{x_4}{c_{11}} \right)^{c_{12}} - 1 \right] Q_{cp} + c_{13} V_{compressor} \quad (3.8)$$

$$\dot{x}_4 = c_{14} \left[1 + c_{15} \left[\left(\frac{x_4}{c_{11}} \right)^{c_{12}} - 1 \right] \right] \left[F_{cp} - c_{16} (x_4 - x_1 - x_2 - c_2) \right] \quad (3.9)$$

The following equation provides an approximation for air flow rate of compressor (F_{cp}), which depends directly on the compressor motor's rotational speed and with respect to supply manifold pressure P_{sm} .

$$F_{cp}(x_3, x_4) = \frac{F_{cp}^{\max} x_3}{x_3^{\max}} \left(1 - \exp \left(\frac{-r \left(s + \left(\frac{x_3^2}{q} \right) - x_4 \right)}{s + \left(\frac{x_3^2}{q} \right) - x_4^{\min}} \right) \right) \quad (3.10)$$

Table A1 provides information on the system parameters, and Table A1 in Appendix 1 defines the coefficients, which range from c_1 , c_2 , c_{16} , which are constants. Future more the modelling of the system is done in different stages to get the required results for the proposed objectives.

Finding the appropriate process model is essential before designing a control-based structure for any sort of process. In the process industries, Model Predictive Control (MPC) has come to be the acknowledged approach for challenging restricted multivariable control issues. In this article design a suitable first order time delay system that corresponds to the higher order system. Then verify the model using step response. For the tuning purpose, a PI controller based on SIMC technique has been designed. Also use the FOMCON Toolbox to create a non-integer order model as well. The nonlinear PEM fuel model is simulated using SIMULINK from MATLAB.

The fuel cell non-linear model is linearised at the operational point with respect to the manipulated variable, $V = 160$ V. In the measured input disturbance given as current, $I = 198$ A. The nonlinear model is linearised around the proposed specific steady-state operating point to make controllers. Each nonlinear equation $f_i(x,u)$ is approximated by its first-order Taylor series expansion around (x_0, u_0) :

$$\begin{aligned} \dot{x} &\approx A(x - x_0) + B(u - u_0) \\ y &\approx C(x - x_0) \\ A &= \left[\frac{\partial f_i}{\partial x_j} \right]_{(x_0, u_0)} ; B = \left[\frac{\partial f_i}{\partial u} \right]_{(x_0, u_0)} ; C = \left[\frac{\partial y}{\partial x} \right]_{(x_0, u_0)} \end{aligned}$$

Equations (3.11) and (3.12) represent the model's state space without perturbations input.

$$x(t+1) = Ax(t) + Bu(t) \tag{3.11}$$

$$y(t) = Cx(t) + Du(t) \tag{3.12}$$

Where $x(t)$ represents the supply pressure (Pa) and $u(t)$ represents the compressed air voltage (V). The framework matrices for PEM fuel cell single input single output are as follows.

$$A = \begin{bmatrix} -10.85 & -7.671 & 0 & 7.65 \\ -28.69 & -32.32 & 0 & 28.94 \\ 0 & 0 & -7.329 & -0.040 \\ 19.84 & 19.84 & 89.95 & -2147 \end{bmatrix} \quad (3.13)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 365.7 \\ 0 \end{bmatrix} \quad C = [0 \ 0 \ 0 \ 1] \quad (3.14)$$

Each term has a physical basis:

- A11,A12: Coupling of oxygen/nitrogen pressures.
- A33: Compressor speed decay due to damping.
- A43: Effect of compressor speed on manifold pressure.
- B3: Direct effect of compressor voltage on compressor speed.
- C4: Output depends on manifold pressure only.

Matrix	Basis of selection or Formation
A	Obtained by linearizing the nonlinear state equations (3.6-3.9) around a steady-state point; elements are partial derivatives $\partial f_i / \partial x_j$. It defines system dynamics.
B	Derived from $\partial f_i / \partial u$; represents how compressor voltage (input) affects the system states.
C	Selected based on measured output variable (supply manifold pressure), so $C = [0 \ 0 \ 0 \ 1]$
D	Zero because no instantaneous effect of input on output. So $D = 0$.

This state space model which is derived above is now converted as first order with respect to time delay (FOPTD) system using the new approach of sub optimal order reduction technique (Chinesta et al., 2016). The concept of performance tuning model identification algorithms is simple. The model-based reduction problem is simply transformed into a measurement optimization difficulty by minimising the state space model. However, due to the delay term, above that the technique can't be used directly in our case. $H(s)$ can be rationalised by using the Padé approximate solution for the time delay. Because the time-based delay term is then

replaced by its Padé estimation, the optimization-based method that should be made reference with respect to the reduction technique for suboptimal model.

It might be difficult to analyse activities with higher-order models. The First Order with respect to Time Delay (FOPTD) model is commonly used to approximate higher-order transfer function models since it is straightforward to evaluate. Process interaction curve technique is used to estimate the FOPTD model. Equation (3.15) provides the method for determining the parameters of the FOPTD model:

$$G(S) = \frac{Ke^{-\varphi s}}{\tau s + 1} \tag{3.15}$$

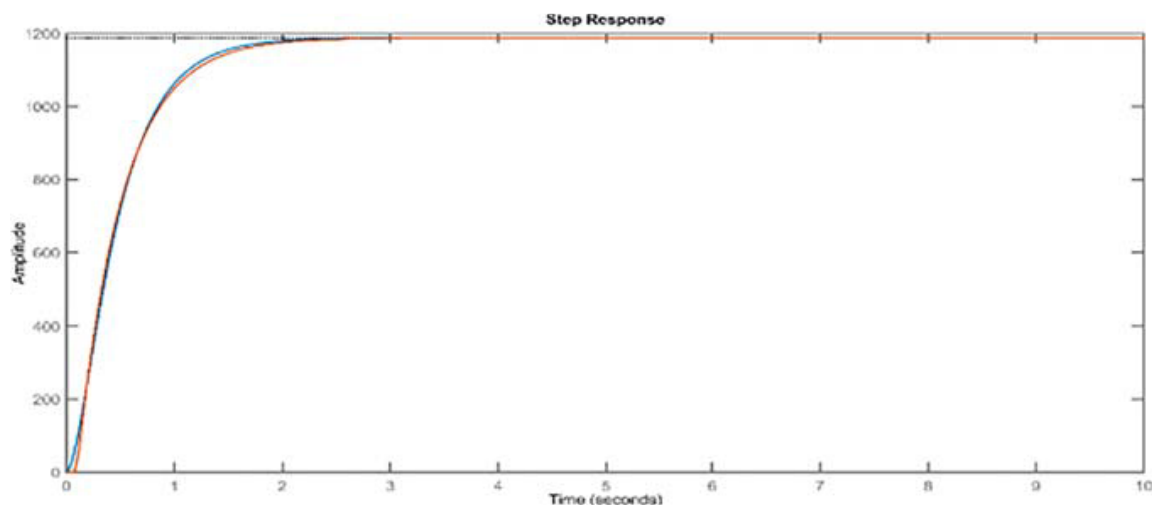


Figure 3.1 Step response of the FOPTD system

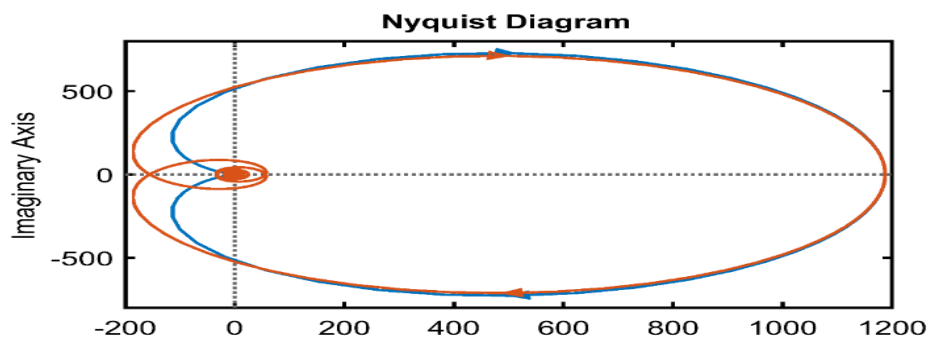


Figure 3.2 Nyquist diagram of FOPTD system

To obtain the parameter of FOPDT the following equations are used as stated in next line:

$$\text{Time delay} \quad \varphi = 1.3t_1 - 0.29t_2 \quad (3.16)$$

$$\text{Time constant} \quad \tau = 0.67(t_2 - t_1) \quad (3.17)$$

These two equations help figure out the time delay (Φ) and time constant (τ) of the First Order Plus Time Delay (FOPTD) model, which is a way to model the nonlinear behavior of PEM fuel cells. The following FOPTD model was used to approximate the nonlinear dynamics of PEM Fuel based cell model as

$$G(s) = e^{-0.0955s} \frac{2821.3}{s + 2.375} \quad (3.18)$$

Check the first order model and higher order model time domain response using step input in figure 3.1. Examine the frequency domain response as well in figure 3.2. It can be observed that a satisfactory outcome for the both the cases.

3.1.3 Algorithm to develop a fractional model to design controller

The systematic processes needed to find a fractional-order (FO) based model by using the MATLAB FOMCON associated toolbox. The input-based signal is essential for system related identification since it regulates the model's output properties. When viewed in this light, it also establishes whether the system is cognizable and the accuracy of identification findings. To obtain more built-in features, different systems require various ideal excitation signals. To simulate the non-integer order system, a number of input signals are chosen, including the saw tooth wave signal, variable frequency signal (VFS), pseudo-random binary sequence (PRBS). In this problem we used PRBS as test signal. Additionally, all of the excitation signals have amplitudes of 1 and have data lengths of 1,000. Because of the sensor accuracy and interference effects, the resulting data are generally tainted by noise in engineering practise. The input data are noise-free, and the output is combined by Gaussian

white noise to more closely resemble the real world. The approach that is most frequently used to define Signal to Noise Ratio (SNR) is as follows:

$$SNR = 10 \log_{10} \frac{YW}{NW}$$

Where YW , NW express the system powers of noise and signal respectively.

External stimulation plays a significant role in determining how accurately a system is identified. This paper uses PRBS as the test signal to investigate how excitation affects detecting non integer order systems. It is clear from Figure 3.3 that it depicts the input and output of the system during PRBS excitation. The fractional zero and pole polynomials of the identified model are provided in the symbolic style. With different options to fix throughout the polynomial, the mathematical framework is identified with static gains to unity and fractional pole polynomials. A model of a first estimate is developed. To do this, define a different-order q such that $0.01q^2$, the polynomial order simultaneously, is used to generate polynomials individually. A plot that displays a good fitting result and shows the identified system's steady behaviour should be exhibited at the conclusion of the identification process. As a result of the satisfactory findings, the model is saved for use in creating a controller. Figure 3.4, show the algorithm chart for the experimental flow. The following identifying non integer model represented as

$$G(s) = \frac{1}{0.00038353s^{1.1854} + 0.00087687s^{0.0086269}} \quad (3.19)$$

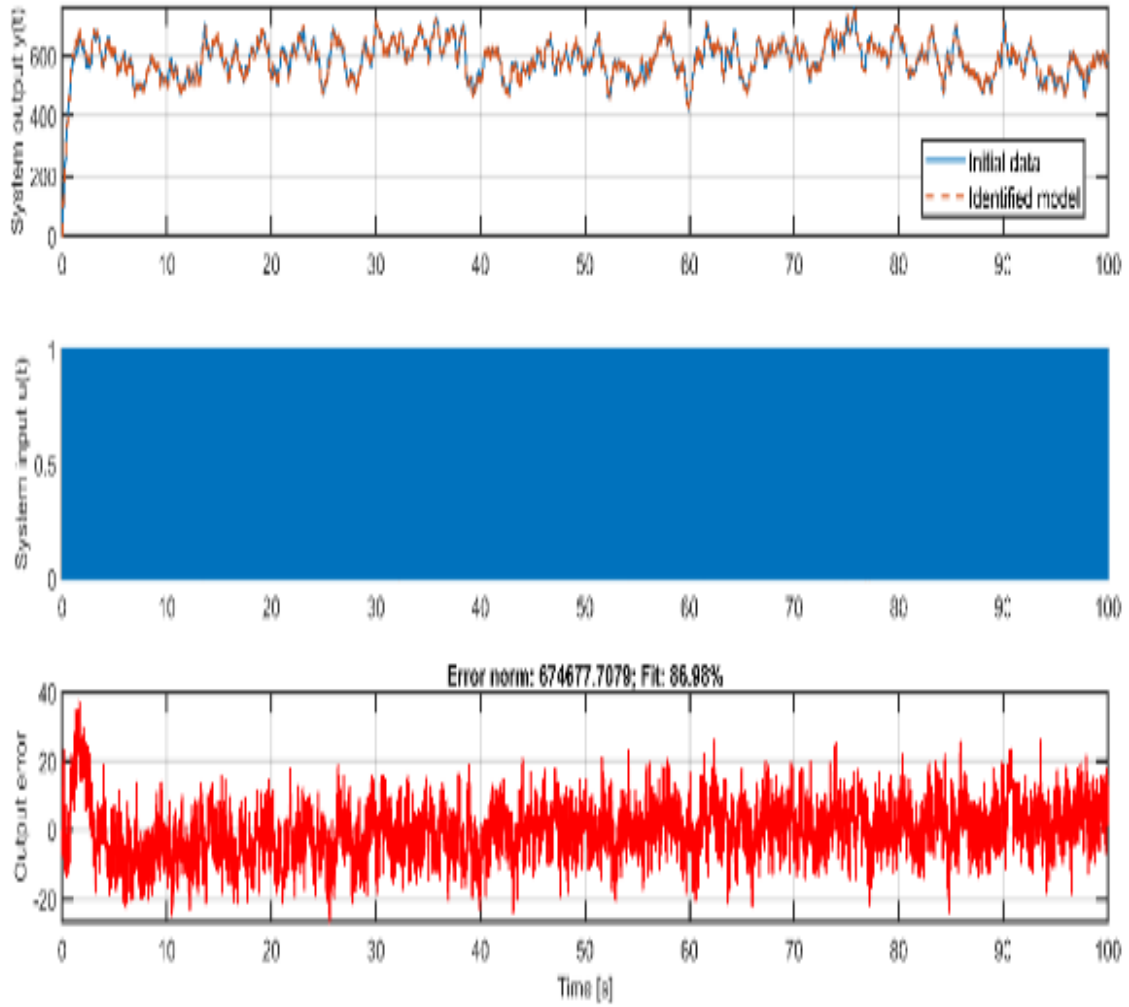


Figure 3.3 System identification for non-integer order system

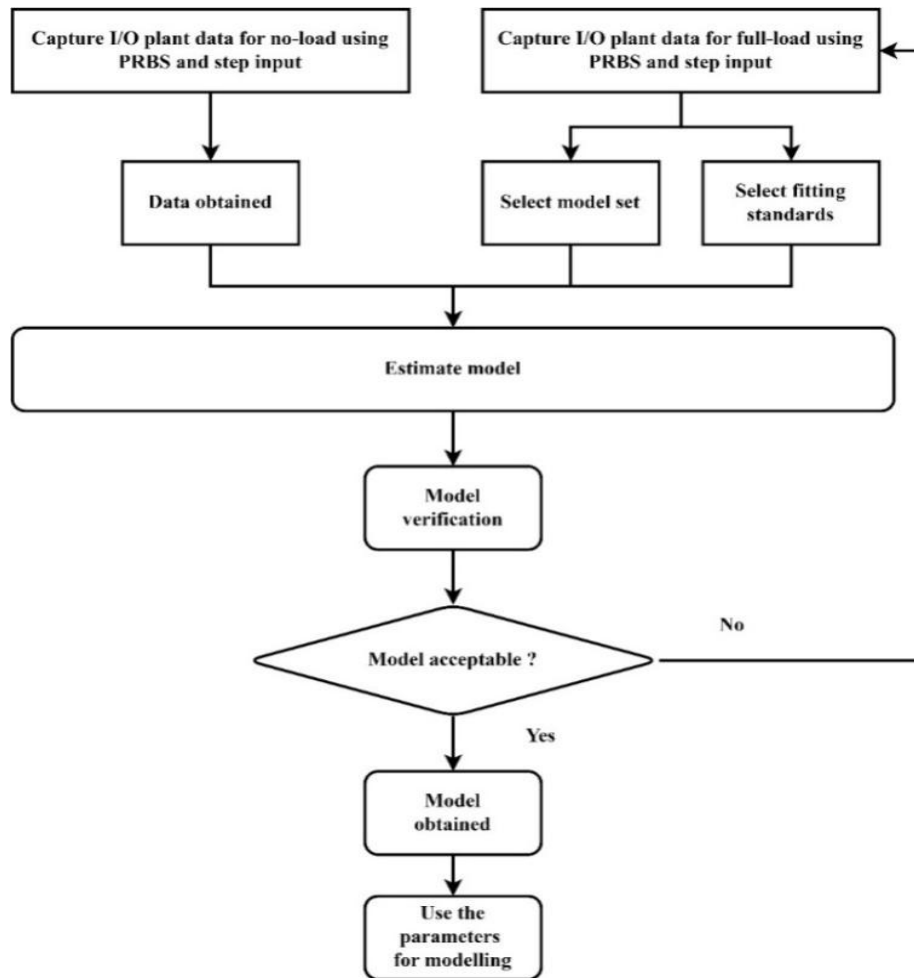


Figure 3.4 Algorithm steps for identifying a fractional order (FO) model

The modelling of the system is done in different stages to get the required results for the proposed objectives.

Stage 1: An integral proportional controller design

The optimal models assume that proportional integral (PI) is the basic default controller. The error loops are taken into consideration, which use a PI controller to regulate the oxygen air pressure. The literature contains a variety of techniques for designing PI controllers. In this work, credible SIMC regulations from Grimholt and Skogestad (2012) are used. The common sub optimal order reduction strategy outlined in the algorithm to generate an IO model,

presented in this form, is used to derive a first-order with respect to time delay (FOPTD) model (G_s) in the first phase of developing controllers using this method.

$$G_p = \frac{K_p}{T^*S + 1} e^{-L^*S} \quad (3.20)$$

The acknowledged process model uses the abbreviations K_p , L , and T to represent for the steps of gain, delay time, and time constant, respectively. For the first-order with delay (FOPDT) process, we looked at the original SIMC tuning algorithm in Eq. 3.21.

$$K_c = \frac{1}{K_p} \frac{T}{T_c + L} \quad \text{and} \quad T_i = \min \{T, 4(T_c + L)\} \quad (3.21)$$

A configurable tuning component called the closed-loop time constant, often known as parameter T_c , is employed to achieve the appropriate trade-off between robustness, efficiency, and input utilization. According to (Grimholt et al., 2012) "tight control" (excellent performance) and reasonable robustness are both indicated by $T_c = L$.

Stage 2: The construction of a fractional proportional integral controller

Also utilised for the same basic FOPTD model is the fractional proportional based integral (FPI) controller. Research projects on adjusting FPI controllers provide a number of tuning suggestions for creating FPID parameters, such as regulatory gain K_c , integral constant for time T_i , and fractional order. The related fractional controller transfer function model is given, after the Laplace transformation.

$$G_c = K_c + \frac{K_i}{S^\alpha} = K_c \left(1 + \frac{1}{T_i S^\alpha} \right) \quad (3.22)$$

Since then, a lot of work has been put into developing fractional-order PID controllers. Early studies were done by (Podlubny 1994). Monje et al., (2008) also design few fraction order controller tuning strategy. The relative dead time (τ) of the system, which is defined as in Eq. (3.23), is a crucial parameter in the FOPDT model that was identified in Eq.(3. 22)

$$\tau = \frac{L}{L+T} \quad (3.23)$$

Systems with $L \gg T$ are said to as delay related dominancy, whereas those with $T \gg L$ are referred to as lag dominated. The " τ " ranges from 0 to 1. As a result, the tuning parameters are below Equations.3. 24, 3.25 and 3.26.

$$K_c = \frac{1}{K_p} \left(\frac{0.2978}{\tau + 0.000307} \right) \quad (3.24)$$

$$T_i = T \left(\frac{0.8578}{\tau^2 - 3.402\tau + 2.405} \right) \quad (3.25)$$

$$\alpha = \begin{cases} 1.1 & \text{if } \tau \geq 0.6 \\ 1.0 & \text{if } 0.4 \leq \tau < 0.6 \\ 0.9 & \text{if } 0.1 \leq \tau < 0.4 \\ 0.7 & \text{if } \tau < 0.1 \end{cases} \quad (3.26)$$

3.1.3.1 Integer order plant with integer order controller

In order to apply an integer-order (IO) controller to an initial more advanced PEM cell model, an IO model in transformed into first order with time delay form. It is provided the plant model as:

$$G(s) = e^{-0.0955s} \frac{2821.3}{s + 2.375} \quad (3.27)$$

The corresponding controller is tuned using original SIMC rules.

Controller tuning $K_p=0.0019$ and $\tau_c=0.4200$

Finally, the controller is:

$$H(s) = 0.0019 \left(1 + \frac{1}{1 + 0.42 * S} \right) \quad (3.28)$$

3.1.3.2 Fractional order controller-based Integer order plant

The fractional-order based controller was calculated using the Chen approach for the same IO plant. We configure the fractional PI controller according to the relative dead time of the system.

Fractional controller tuning $K_p=0.0014$, $K_i=0.007038$, $\lambda=0.9$

The fractional order controller is:

$$H(S) = 0.0014 \left(1 + \frac{1}{1 + 0.007038s^{0.9}} \right) \quad (3.29)$$

3.1.3.3 Fractional order plant with fractional order-based controller

A FO model plant is found using the FOMCON toolbox (algorithm to construct a FO model), as was previously explained. The time domain technique is used to identify the fractional-order (FOTF) model using the “outer loop filter approximation.” The stable FOTF model is given by:

$$G(s) = \frac{1}{0.00038353s^{1.1854} + 0.00087687s^{0.0086269}} \quad (3.30)$$

The “interior point” approach is then used to optimise the fractional-order PI controller while selecting ISE as the performance metric. The FPI controller is optimised after choosing the minimum and through maximum permitted values for each tuning parameter. The FPI

controller is optimised after choosing the lowest and maximum permissible values for each tuning parameter. The adjusted variables are

Fractional controller tuning $K_p=0.0014$, $K_i=0.016364$, $\lambda=1.1899$

The below information is for the fractional order controller for the fractional order plant:

$$H(S) = 0.0014 \left(1 + \frac{1}{1 + 0.016364s^{1.1899}} \right) \quad (3.31)$$

This section essentially uses a fourth-order scheme. Compressor angular speed, supply heat exchanger air pressure, partial oxygen pressure, and partial nitrogen pressure are among the states taken into consideration. Finally create a controller of both integer and fractional order for the fourth-order PEMFC system. For the same PEMFC system create a fractional controller and a fractional plant as well. The main problem with this modelling is that it makes the assumption that system dynamics only depend on these four states. Practically other state are also play an important role in system dynamics. The partial pressure of hydrogen as a state is also taken into consideration in the next section since it is crucial to maximising efficiency. In addition, take into account the mass flow rate of hydrogen and oxygen. In addition, water pressure at the anode side is regarded as a state. Create a new 7th order PEMFC model taking this situation into consideration.

3.2 Mathematical model of 7th order PEMFC with problem statement

This section is divided in to three subsections, the first include the mathematical model of 7th order PEMFC, the second includes the linearization of non-linear dynamics of the fuel cell and the third subsection includes the problem statement due to the non-linear dynamics of the fuel cell. Although the 9th-order model is physiologically true, it is overly complex for control design, particularly when real-time pressure control or controller tuning is required

(PI/PID, MPC, etc.).As a result, researchers (Suh 2006) reduce the system to a 7th- or 4th-order "control-oriented" model that captures the main dynamics while excluding slow or weakly connected subsystems.

3.2.1 Mathematical modelling of PEMFC

The PEMFC consists of three main components: the first is anode which act as fuel inlet, the second is electrolyte and the third is cathode which helps sufficient air to pass through the PEMFC for electrochemical reaction as shown in the figure 3.5. At anode side the hydrogen acting as fuel is split in to hydrogen ion and a free electron in the present of platinum catalyst. After splitting, the electron moves through the external connected circuit and hydrogen ion moves to cathode through the proton exchange membrane. The reaction on anode side is expressed as:

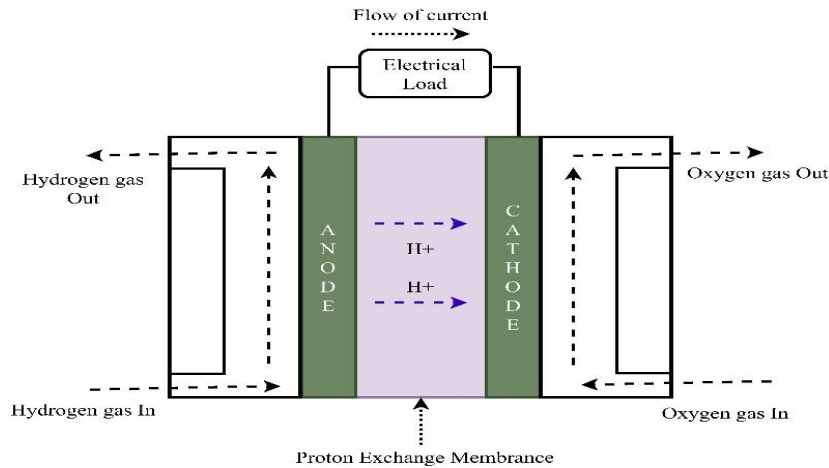


Figure 3.5 PEMFC working diagram (Routh et al., 2023)

At the cathode, electrons and hydrogen ions react with oxygen, producing water as a by-product that flows out of the fuel cell. At the cathode, the reduction reaction is:



The output voltage of a PEMFC is primarily determined by operating conditions such as stack temperature, partial pressure, humidity, and mass flow rate of hydrogen and oxygen, as well as load variation. The polarisation curve primarily demonstrates the static characteristics of a fuel cell. The output voltage decreases nonlinearly as the current density increases. The open circuit voltage of a PEM Fuel cell is as follows (Nernst, W. (1889)):

$$V_{O,FC} = n_s \cdot E_0^{Cell} + \frac{n_s RT}{2F} \ln \left[\frac{P_{H_2} \cdot (P_{O_2})^{0.5}}{P_{H_2O}} \right] \quad (3.34)$$

Where, P indicates the partial pressure of the corresponding elements, V indicate the voltage of the fuel cell, E is related to the open-circuit voltage of one cell, R represent universal gas constant, T highlights stack temperature, n is the number of fuel cell and F is faradays constant. Now, when the fuel cell is connected to provide electrical energy for any application it faces three types of losses as stated below:

Activation losses: These losses occur due to the sluggish nature of electrode kinematics at lower current density.

Ohmic losses: It's the most common losses occur in every electrical circuit. But in case of fuel cell, it occurs due to resistive properties of cathode and anode.

Concentration losses: This occurs due to formation of concentration gradients due to presence of reactance on the surface of the electrodes.

So, the actual output voltage of the fuel cell is modified taking into consideration of the above losses.

$$V_{fc} = V_{O,FC} - n_s \cdot (V_{loss}^{Act} + V_{loss}^O + V_{loss}^{Conc}) \quad (3.35)$$

$$V_{loss}^{Act} = a_0 + T[a + b \ln(I)] \quad (3.36)$$

$$V_{loss}^O = IR_{ohm} \quad (3.37)$$

$$V_{loss}^{Conc} = -\frac{RT}{eF} \ln\left(1 - \frac{I}{I_L}\right) \quad (3.38)$$

The difference between oxygen and hydrogen flowing inside and outside the cathode and anode determines the net mole flow rate of oxygen and hydrogen. The flow rates do not change instantly as the variable load changes. We can calculate the net mole flow rate of oxygen and hydrogen based on the transportation lag.

$$\frac{d(M_{O_2})_{net}}{dt} = \frac{1}{\lambda_C} \left(\frac{I}{4F} - (M_{O_2})_{net} \right) \quad (3.39)$$

$$\frac{d(M_{H_2})_{net}}{dt} = \frac{1}{\lambda_A} \left(\frac{I}{2F} - (M_{H_2})_{net} \right) \quad (3.40)$$

According to the ideal gas equation $PV=nRT$, the partial pressure of each gas depends on the amount of gas in the cell. The amount of gas within the cell is equal to the inflow rate of gas minus the gas consumption rate and the gas outlet flow rate. Thus, the state equations are

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_a} (W_{H_2}^{in} - W_{H_2}^{out} - W_{H_2}^{used}) \quad (3.41)$$

$$\frac{dP_{H_2O_A}}{dt} = \frac{RT}{V_a} (W_{H_2O_A}^{in} - W_{H_2O_A}^{out} - W_{H_2O_A}^{membrane}) \quad (3.42)$$

$$\frac{dP_{O_2}}{dt} = \frac{RT}{V_c} (W_{O_2}^{in} - W_{O_2}^{out} - W_{O_2}^{used}) \quad (3.43)$$

$$\frac{dP_{N_2}}{dt} = \frac{RT}{V_c} (W_{N_2}^{in} - W_{N_2}^{out}) \quad (3.44)$$

$$\frac{dP_{H_2O_c}}{dt} = \frac{RT}{V_c} (W_{H_2O_c}^{in} - W_{H_2O_c}^{out} + W_{H_2O_c}^{produced} - W_{H_2O_c}^{membrane}) \quad (3.45)$$

Where, $W_{H_2O_a}^{membrane}$ and $W_{H_2O_c}^{membrane}$ represent the water vapor used to humidity the membrane from the anode and cathode side. In this model, the state variables represent the mass flow rate of hydrogen and oxygen at the anode and cathode, pressure of hydrogen and water vapour at the anode, and pressure of oxygen, nitrogen, and water vapour at the cathode, respectively.

$$\begin{aligned} x(t) &= [M_{O_2} \quad M_{H_2} \quad P_{H_2}(t) \quad P_{H_2O_a}(t) \quad P_{O_2}(t) \quad P_{N_2}(t) \quad P_{H_2O_c}(t)]^T \\ &= [x1(t) \quad x2(t) \quad x3(t) \quad x4(t) \quad x5(t) \quad x6(t) \quad x7(t)]^T \quad (3.46) \\ &= [x1(t) \quad x2(t) \quad x3(t) \quad x4(t) \quad x5(t) \quad x6(t) \quad x7(t)]^T \end{aligned}$$

The state space equations are given by

$$\dot{x} = f_1(x)u_a + f_2(x)u_c + g(x)I \quad (3.47)$$

Now the modelling of 7th order PEMFC is stated below through the equations:

$$\begin{aligned}\dot{x}_1 &= \left(\frac{-1}{\lambda_c}\right)x_1 + \left(\frac{1}{4\lambda_c F}\right)I \\ \dot{x}_2 &= \left(\frac{-1}{\lambda_A}\right)x_2 + \left(\frac{1}{2\lambda_A F}\right)I \\ \dot{x}_3 &= \frac{RT\lambda_{H_2}}{V_a} \left(Y_{H_2} - \frac{x_3}{x_3+x_4}\right)k_a u_a + \frac{RTC_1}{V_a} \left(\frac{x_3}{x_3+x_4} - 1\right)I \\ \dot{x}_4 &= \frac{RT\lambda_{H_2}}{V_a} \left(\frac{\varphi_a P_{vs}}{x_3+x_4 - \varphi_a P_{vs}} - \frac{x_4}{x_3+x_4}\right)k_a u_a + \frac{RTC_1}{V_a} \left(\frac{x_4}{x_3+x_4} - 1\right)I \\ \dot{x}_5 &= \frac{RT\lambda_{air}}{V_c} \left(Y_{O_2} - \frac{x_5}{x_5+x_6+x_7}\right)k_c u_c + \frac{RTC_1}{2V_c} \left(\frac{x_5}{x_5+x_6+x_7} - 1\right)I \\ \dot{x}_6 &= \frac{RT\lambda_{air}}{V_c} \left(Y_{N_2} - \frac{x_5}{x_5+x_6+x_7}\right)k_c u_c\end{aligned}$$

The final 7th order equation can be expressed as:

$$\dot{x}_7 = \frac{RT\lambda_{air}}{V_c} \left(\frac{\varphi_a P_{vs}}{x_5+x_6+x_7 - \varphi_a P_{vs}} - \frac{x_5}{x_5+x_6+x_7}\right)k_c u_c + \frac{RTC_1}{V_c} \left(\frac{C_2}{C_1} \left(1 - \frac{x_5}{x_5+x_6+x_7}\right) - 1 - \frac{x_5}{x_5+x_6+x_7}\right)I \quad (3.48)$$

The model output variables are defined as

$$y(t) = \begin{bmatrix} P_{H_2}(t) \\ P_{O_2}(t) \end{bmatrix} = \begin{bmatrix} x3(t) \\ x5(t) \end{bmatrix} \quad (3.49)$$

The system control input is given by $u(t) = [u_a(t) \quad u_c(t)]^T$

Where,

$$\begin{aligned}u_a(t) &= \frac{1}{k_a} (H_{2in}(t) + H_2 O_{Ain}(t)) \\ u_c(t) &= \frac{1}{k_c} (O_{2in}(t) + N_{2in}(t) + H_2 O_{Cin}(t))\end{aligned}$$

3.2.2 Linearization of non-linear PEMFC

Linearising the fuel cell dynamic is a quite complex process. The liberalized system that approximates the nonlinear system in the vicinity of the equilibrium point can be written in matrix form using the Jacobian linearization method (Ababneh et al., 2011).

$$\Delta x'(t) = J\Delta x(t) + K\Delta u(t) + L\Delta I(t) \quad (3.50)$$

In the equation 3.50 the constant Jacobian matrices are defined as follow:

$$J = \frac{\partial f}{\partial x} \rightarrow f(x, u, I) \rightarrow \begin{bmatrix} J1 & 0 \\ 0 & J2 \end{bmatrix} \in x = x, u = u, I = I \quad (3.51)$$

Where to linearize the system the matrix $J1$ and $J2$ are represented as a combine matrix:

$$J = \begin{bmatrix} j11 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & j22 & 0 & 0 & 0 & 0 & 0 \\ j31 & j32 & 0 & 0 & 0 & 0 & 0 \\ j41 & j42 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & j53 & j54 & j55 & 0 & 0 \\ 0 & 0 & j63 & j64 & j65 & 0 & 0 \\ 0 & 0 & j73 & j74 & j75 & 0 & 0 \end{bmatrix} \quad (3.52)$$

In, the similar manner the matrix K is defined as follow:

$$K = \frac{\partial f}{\partial u} \rightarrow \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k13 & 0 \\ k14 & 0 \\ 0 & k25 \\ 0 & k26 \\ 0 & k27 \end{bmatrix} \quad (3.53)$$

As a result, the matrix L is obtained as follows:

$$L = \frac{\partial f}{\partial u} \rightarrow [l_1 \ l_2 \ l_3 \ l_4 \ l_5] \tag{3.54}$$

The linearized system corresponding to the above equations is given by,

$$\delta f_c(t) = J\delta_x(t) + K\delta_u(t) + L\delta_I(t) \tag{3.55}$$

Now, by obtaining the value of the matrices the observability and controllability of the system can be easily calculated.

3.2.3 Problem formation due to dynamics of PEMFC

Even though PEMFC non-linear equations are linearized, the dynamics still play the important role in the designing of the controller and control strategies. The dynamics of fuel cell is due to “charge double layer” phenomenon. In this phenomenon, when two charged materials are in contact then charges are accumulated on their surface, this charged is stored and act as parallel capacitor. The equivalent diagram can be shown through figure 3.6.

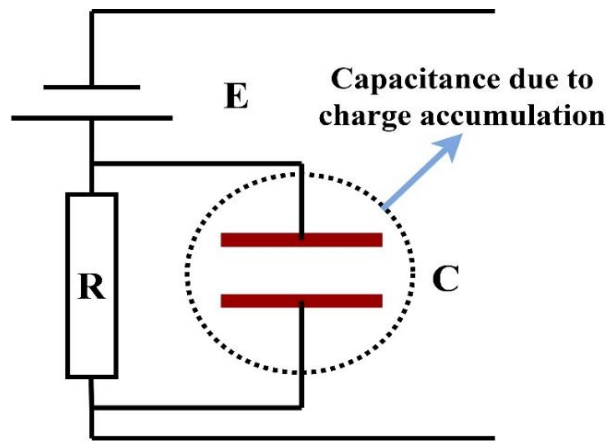


Figure 3.6 Equivalent circuit diagram for dynamics of PEMFC

In the presence of capacitance in the PEMFC model the dynamics of the fuel cell is expressed as the effect of capacitance which is expressed as:

$$V_{C,FC} = (I - C \frac{dV_{C,FC}}{dt})(R_{all}) \quad (3.56)$$

Using equation 3.56 and implementing it into the base equation 3.50 will change the overall state space model of the system as stated below:

$$\delta f_c(t) = J\delta_x(t) + K\delta_u(t) + L\{\delta_i(t)|_{\text{Change in } I}\} \quad (3.57)$$

Having an output ($\tau(t)$) of:

$$\tau(t) = R\delta_x(t) + v(t) \in \{\text{system states}\}, \{\text{noise}\} \quad (3.58)$$

Where C denotes capacitance due to charge layer and v represent the system noise. So, from the above discussion it is clear that the PEMFC non-linear problem is solved by linearizing the system parameters and the dynamics are added in to the state space. This section completes the overall modelling of 7th order PEMFC for real time application. So, the problem occurs due to the PEMFC modelling which are the objective of this research are given below:

After converting non-linear to linear model of PEMFC, how the controller will behave for this new linear model.

3.3 Modelling of proposed fractional $PI^\lambda D^\mu$ controller using genetic algorithm for controlling the PEMFC model

To tackle the non-linear and dynamic model of PEMFC, PID controllers need some more flexibility than the normal controllers. The FPID controllers provide the flexibility by providing two more adaptable parameters to be control. The FPID controller provides robustness in certain input parameters range by non-changing characteristics during those

small changes. As, mentioned in section 3.2 that PEMFC is non-linear and complex dynamics so conventional control strategies provide large time delay and slow control response.

To tackle this proposed FPID controller is integrated with GA, to give accurate optimize parameters (rise time, settling time, peak overshoot etc) and slow response is eliminated.

3.3.1 Modelling of Proposed FOPID

The FOPID controller is based on the fractional calculus, which can be expressed as:

$${}_{\beta}O^{\beta} f(t) = \left\{ \begin{array}{l} \frac{d^{\beta}}{dt^{\beta}} f(t), \in R(\beta) > 0 \\ f(t), \in R(\beta) = 0 \\ \int_{\beta}^t f(\tau)(d\tau), \in R(\beta) < 0 \end{array} \right\} \quad (3.59)$$

Where, the operator O represent the calculus operator and β any real number. Using the Riemann-Liouville's definition the fractional calculus expression of 3.59 can be easily expressed using equation 3.60:

$${}_{\beta}O^{\beta} f(t) = \frac{1}{\Gamma(n-\beta)} \left(\frac{d}{dt} \right)^n \int_{\beta}^t \frac{f(\tau)}{(t-\tau)^{\beta}} d\tau \quad (3.60)$$

Where, Γ represent Gamma function and $n-1 < \beta < n$. Through the equation used above and conventional PID controller, the FOPID is shown in the figure 3.3. The overall mathematical model for FOPID controller can be given as follow:

$$V_{fc}(t) = K_p e(t) + K_i O^{-\lambda} e(t) + K_d O^{\mu} e(t) \quad (3.61)$$

The corresponding output of the given system:

$$C(s) = K_p + K_i s^{-\lambda} K_d s^{\mu}, \in \lambda > 0, \mu < 2 \quad (3.62)$$

Equation 3.61 shows the FPID model in time domain while equation 3.62 express the FOPID model in frequency domain. As shown in the figure 3.7, the PEMFC has two inputs out of which the first input is the disturbance created by the current and the second input is the error in the reference voltage of the PEMFC output. The PH in the diagram represents the hydrogen pressure as the controlling parameter from the FOPID. The error signal is generated during load change.

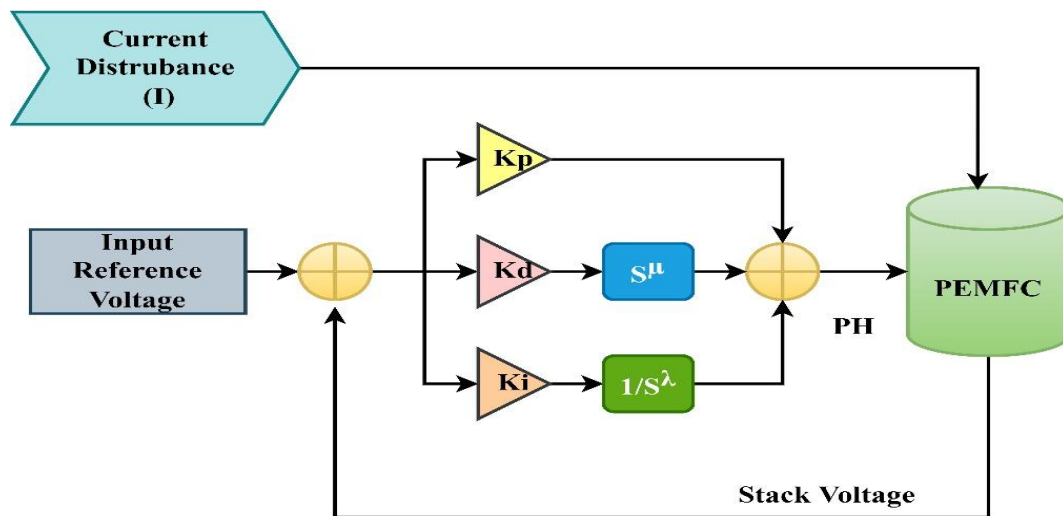


Figure 3.7 FOPID based controller (Routh et al., 2023)

3.3.2 Integrating FOPID with GA

The GA is an optimization technique which can work in multi-dimensional framework to find the optimal solution for a given problem. It's a natural evolution model which use to manipulate the individual system over the populations over several stages and generation to improve the system performance by improvising the environment with better fitness functions. In general, the GA work in the step as shown in the table 3.1.

So for the better performance of PMEFC using the FOPID controller, the GA tune the controller parameters to ensure achievement of objective functions. The overall tuning of FOPID using GA for the PMEFC is shown through flow chart in the figure 3.8. The Genetic

Algorithm (GA) is an evolutionary optimisation technique that determines the most effective settings of a Fractional PID (FOPID) controller by minimising an objective function called Integral Square Error (ISE). Define the FOPID structure with parameters. K_p , K_i and K_d , λ and μ .

$$C(s) = K_p \left(1 + \frac{1}{T_I s^\lambda} + T_D s^\mu \right) \quad (3.63)$$

$$= K_p + \frac{K_i}{s^\lambda} + K_d s^\mu C(s) = K_p \left(1 + \frac{1}{T_I s^\lambda} + T_D s^\mu \right) \quad (\lambda, \mu > 0) \quad (3.64)$$

Set the GA settings (population size, crossover rate, mutation rate, and maximum generation).

Create an initial population of potential solutions (chromosomes) at random.

- Simulate the system for each candidate FOPID controller.
- Compute the objective function (ISE) for each individual:

$$J = \text{ISE} = \int_0^T e^2(t) dt; \text{ where } e(t) \text{ is the error.}$$

Each solution represents a collection of settings for optimising the PEMFC system. Each candidate's fitness is evaluated using an objective function, which is related to efficiency, power output, or error minimisation in PEMFC. Individuals with higher fitness (lower error) are chosen for reproduction in the selection process. Some individuals (indicated with crosses) are eliminated for poor performance. This process ensures that better solutions have a higher chance of passing their characteristics to the next generation. Crossover Selected people undertake a crossover operation to produce progeny. Two parents exchange parts of their genetic material (controller parameters) to produce higher-performing children (new set). This replicates biological reproduction, allowing new solutions to inherit the best characteristics of prior generations. Mutation involves introducing minor random changes in

progeny to preserve diversity and prevent premature convergence. The mutation allows for the exploration of novel solutions that may outperform their parents. Centrally, PEMFC optimisation aims to improve the system's performance. Each generation is tested in a PEMFC setting to determine its fitness.

Table 3.1 Steps involve in GA

Step	Description
1	Assemble the system initial population
2	Calculate and determine fitness of each system
3	While ϵ if acceptable solution not found
	Or ϵ number of generations doesn't exceed
4	Perform reproduction for the next stage of system generation
5	Create new offspring by performing crossover between the parents
6	Implement the mutation with the system probability
7	Calculates the new fitness overall
8	End

In table 3.1 shows the different step involve in genetic algorithm which one is used to optimize the parameter of normal PID controller as well as fractional PI controller to control the pressure of hydrogen and oxygen of PEMFC to get desire output across the load. Apply genetic algorithm in this challenge because it is robust and requires minimal computational time. This two factors that are crucial for real time controller design problem. GA can quickly

and effectively determine the fractional controller parameters which give the minimum integral square error.

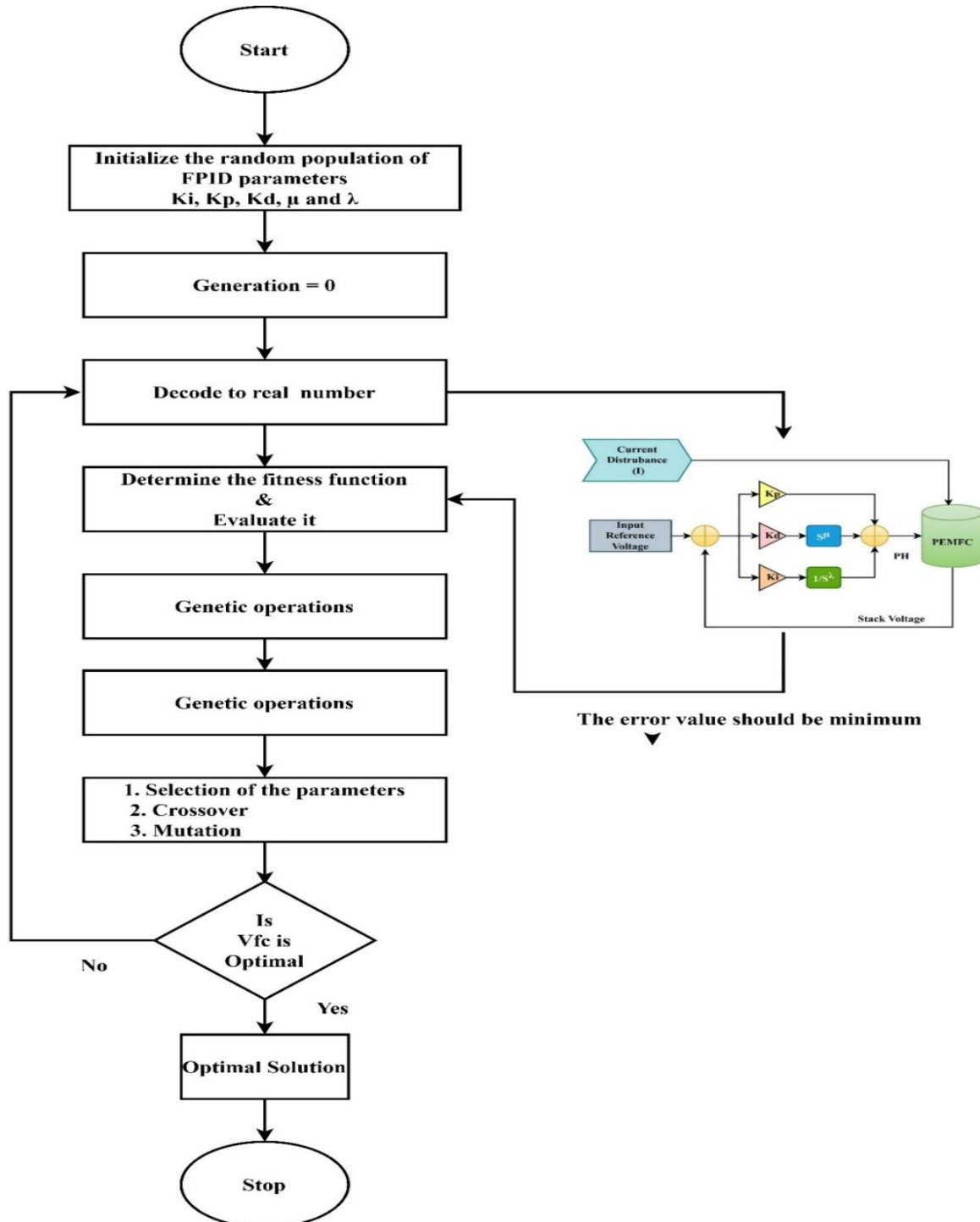


Figure 3.8 Proposed FPID integrated with GA (Routh et al., 2023)

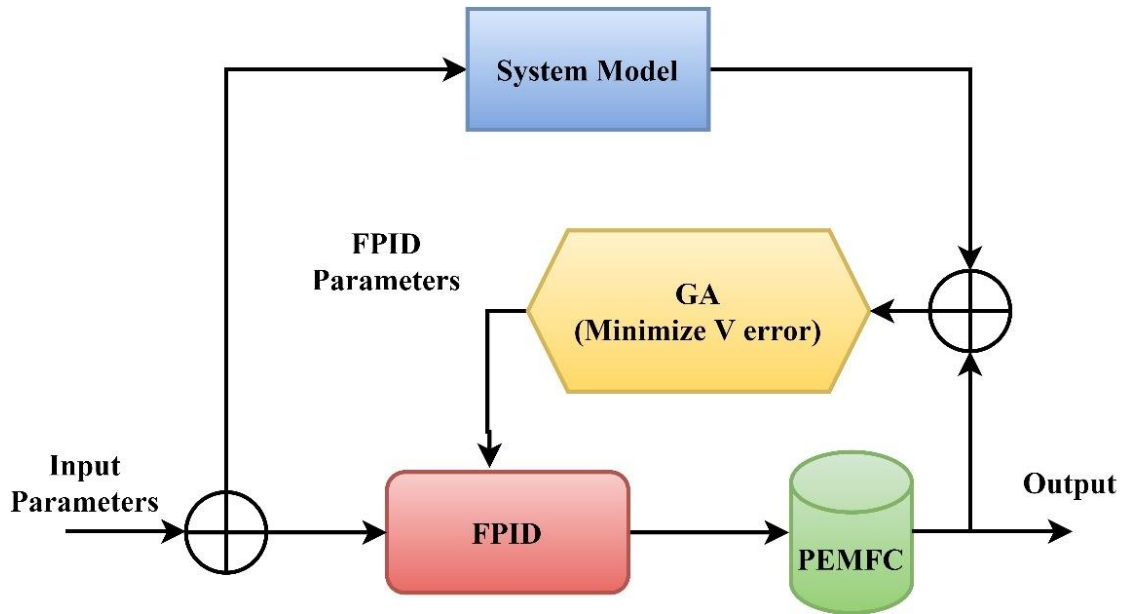


Figure 3.9 Final model integrated with GA

A new 7th order PEMFC model is designed in this section of the thesis. Then use Jacobian linearization approach to linearize this model. Lastly, create a fractional controller to regulate the hydrogen flow rate in order to maximise power across the load. Genetic algorithms lower the integral time error (ITE), integral square error (ISE), integral absolute error (IAE), and integral time square error (ITSE) for PEMFC systems by optimising the parameters related to fractional controllers. This model functions immaculately if the load is not changed often. However, in the actual world, the load could fluctuate suddenly. Forcefully increasing the oxygen and hydrogen flow rate when the load changes quickly could cause the fuel cell membrane to hydrate more. This leads to fuel cell destruction.

In the following design section, a boost converter is designed to raise the voltage level across the load. Therefore, obtaining an appropriate boost converter control system is crucial. This study aimed to improve the performance of PEMFCs by creating simulink models of conventional PI, PI based on particle swarm optimisation (PSO), PSO-based fractional order proportional and integral (FOPI), PI based on genetic algorithms (GA), and GWO-based

FOPI controllers. After that, the performance rates of these methods were contrasted. This thesis's next section initially described several optimisation techniques used in the boost converter. The grey wolf optimisation method can therefore be used to regulate the suggested DC-DC boost converter, resulting in a more effective PEMFC system with improved dynamic performance.

3.4 Optimization methodology approach

This section provides an overview of the research methodologies that were used. The approaches that are deployed for the optimisation of PI parameters include the PEM fuel cell and the traditional PI-controlled DC/DC converter, in addition to the PSO, PSO-based FOPI, and GA-based FOPI approaches. This part also provides an explanation of the modelling approach for GWO-FOPI and its details that were proposed in this research. Additionally, using MATLAB/SIMULINK software for simulation, the total system performance was investigated. For PEMFC, specifically, the Simscape module was utilised.

3.4.1 PEM Fuel Cell

Out of all fuel cells, the PEM fuel cell has the highest energy density. The features of the fuel cell's composition and structure give birth to this predicament. The process of chemical reactions occurring within a fuel cell is the opposite of electrolysis. The PEM fuel cell, which has two metallic electrodes—a positive electrode known as the cathode and a negative electrode known as the anode—is shown in Figure 1 along with its configuration and basic working principles. The figure illustrates how the anode and cathode inputs are used by hydrogen and oxygen, respectively. In the anode section, a catalyst (such as compounds containing platinum) splits hydrogen atoms into protons and electrons. A PEM fuel cell's anode reaction is as follows:

The divided protons travel via the membrane, a proton-conducting electrolyte, while the electric current produced by the electrons' motion travels through the external electrical circuit. Together with clean water vapour, protons travelling through the electrolyte and electrons travelling through the electrical circuit recombine and mix with oxygen. Heat is significant because elevated temperatures have the potential to create thermal stresses that shorten a device's predicted lifespan and cause damage. Inverters can function better and be less prone to damage if the temperature of the power components is accurately modelled and controlled.

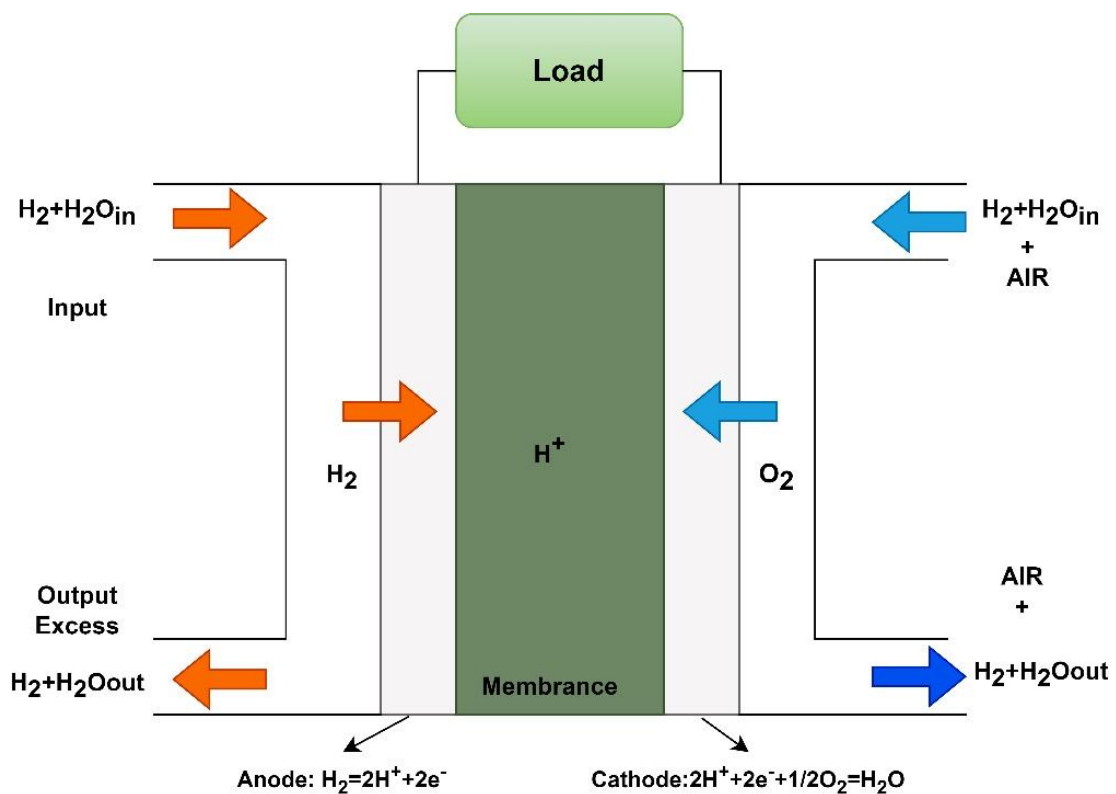


Figure 3.10 PEM Fuel cell basic structures

Thus, real-time temperature control models have obviously been described in the literature (Chen et al., 2022). The PEM fuel cell's overall reactions and cathode reaction are as follows, respectively:



The potential applications of this technology in present and future contexts are well acknowledged. It displays great power density, is lightweight and requires little hardware, can operate at low operating temperatures between 60 and 80 °C, and starts up quickly. It can also adjust to changes in power consumption. The main governing equation of PEM fuel cell is given bellow:

$$\frac{dp_{O_2}}{dt} = \frac{RT_{fc}}{V_{ca} M_{O_2}} \left(Q_{O_2,ca,in} - Q_{O_2,ca,out} - Q_{O_2,reacted} \right) \quad (3.67)$$

$$\frac{dp_{N_2}}{dt} = \frac{RT_{fc}}{V_{ca} M_{N_2}} \left(Q_{N_2,ca,in} - Q_{N_2,ca,out} \right) \quad (3.68)$$

$$\frac{dP_{H_2}}{dt} = \frac{RT}{V_a} (W_{H_2}^{in} - W_{H_2}^{out} - W_{H_2}^{used}) \quad (3.69)$$

$$V_{dc_stack} = V_{open} - V_{ohmic} - V_{act} - V_{con} \quad (3.70)$$

$$V_{open} = N_o \left[V_o + \frac{RT}{2F} \ln \left(\frac{PH_2 \sqrt{PO_2}}{PH_2O} \right) \right] \quad (3.71)$$

$$V_{ohmic} = I_{dc} \cdot R_{FC} \quad (3.72)$$

$$V_{act} = N_o \frac{RT}{2\alpha F} \ln \left(\frac{I_{dc}}{I_o} \right) \quad (3.73)$$

$$V_{con} = -c \ln \left(I - \frac{I_{dc}}{I_{Lim}} \right) \quad (3.74)$$

3.4.2 The Conventional PI Controlled DC/DC Converter

The typical Proportional-Integral (PI) regulated DC/DC converter is a fundamental component in power electronics, used to regulate the output voltage or current in numerous applications such as power supplies, battery charging, and renewable energy systems. The PI controller, which combines proportional and integral actions, ensures that the converter's output remains steady despite variations in load or input voltage. The proportional component responds immediately to the error signal (the difference between desired and actual output), but the integral component reduces steady-state faults by integrating the error over time. This combination gives a balanced approach to attaining both rapid reaction and negligible steady-state error, making the PI controller particularly successful for DC/DC converters.

In a conventional DC/DC converter setup, the PI controller is included into the feedback loop. The output voltage is continuously measured and compared to a reference value. The error signal created from this comparison is supplied into the PI controller, which modifies the duty cycle of the converter's switching element (such as a transistor) correspondingly. This adjustment controls the energy flow from the input to the output, ensuring the desired voltage is maintained. The picture below displays a simple schematic of a standard PI-controlled DC/DC converter, illustrating the feedback mechanism and the role of the PI controller in regulating the output. Figure 3.11, shows the basic block of DC/DC converter.

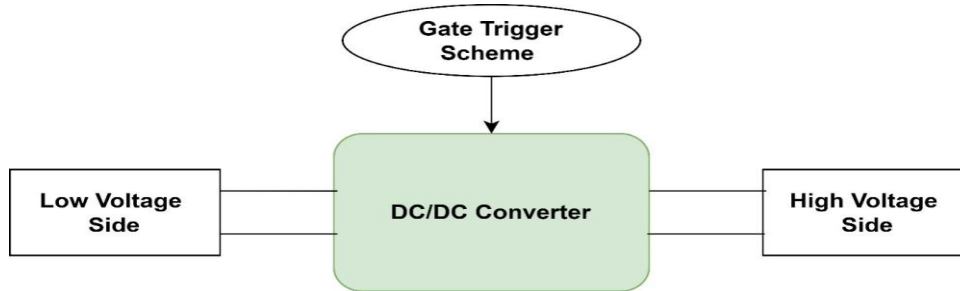


Figure 3.11 DC/DC converter basic block

3.4.3 Fractional order proportional and integral (FOPI) controller

Fractional Order Proportional and Integral (FOPI) controllers extend the classic PI controllers by introducing the concept of fractional calculus, allowing for non-integer order differentiation and integration. This enhancement increases flexibility and control, allowing for more exact tuning and performance in complex and dynamic systems. The FOPI controller's structure consists of a proportional and an integral term, both raised to fractional orders, as well as the differentiation and integration orders. This versatility enables the FOPI controller to provide more accurate and robust responses than its integer-order counterpart, particularly in systems with long memory and hereditary features.

The adoption of FOPI controllers in actual applications such as power systems, robotics, and industrial processes has demonstrated considerable increases in performance measures like transient responsiveness, stability, and robustness against disturbances. The FOPI controller's capacity to fine-tune the system's response by modifying fractional orders allows for more nuanced control, which is especially useful in systems with nonlinearities or time-varying dynamics. Despite its benefits, the FOPI controller necessitates more advanced mathematical tools for design and analysis, and its implementation might be computationally demanding. However, as digital signal processing and computational capabilities progress, the practical

deployment of FOPI controllers becomes more viable, providing a formidable tool for today's control engineering difficulties.

The primary goal of this proposed work is to keep the voltage across the load constant in the event that the PEMFC's output voltage fluctuates. For this reason, a DC-DC boost converter was designed. Create a standard PI controller first, then alter the duty cycle to optimise the settling time, rising time, and peak overshoot when the input side voltage changes. Lastly, to improve performance over PI controllers, develop a fractional PI controller for the boost converter.

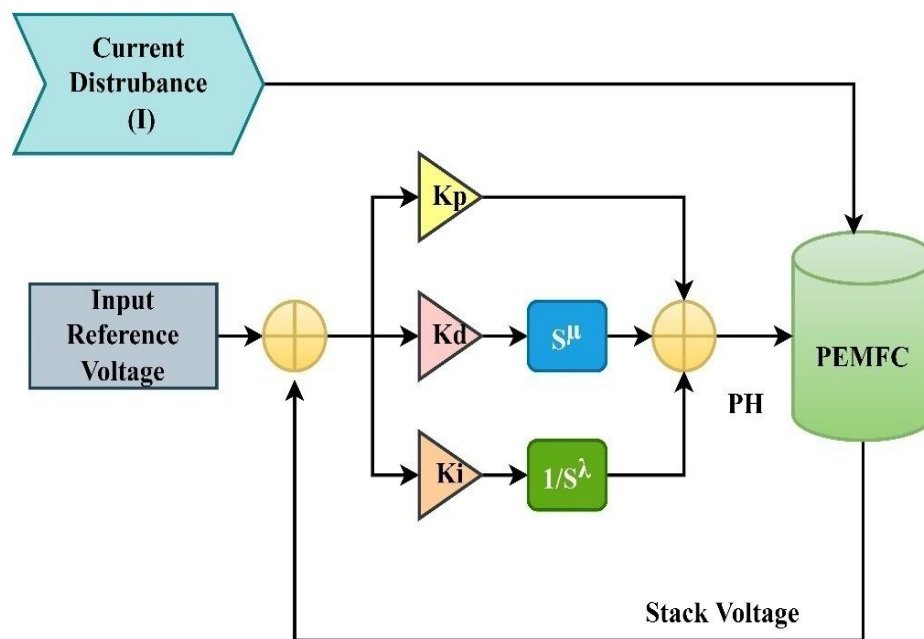


Figure 3.12 FOPI block diagram for PEM Fuel Cell (PEMFC)

Create a fuel cell stack using equations 3.67 to 3.74 in accordance with the modelling described above. A DC-DC boost converter then connected to this fuel cell stack in order to provide a steady voltage across the load. For this dc-dc converter, first develop a standard PI controller using the SIMC rule. Finally, create a fractional controller for a DC-DC boost

converter using the Chen approach. Table 3.2 provide the parameter value correspond to PI and fractional PI controller.

Table 3.2 Conventional & FOPI model values

Methodology	Kp	Ki	λ
Conventional PI	0.002	0.18	
FOPI	0.42	0.9	0.2

3.4.4 Particle swarm optimization (PSO) and PSO-based FOPI (PSO-FOPI) controller

Particle Swarm Optimization (PSO) is a famous and frequently used computer method that is modeled after the social behavior of birds flocking or fish schooling. PSO, invented by Kennedy and Eberhart in 1995, is a population-based optimization technique that seeks the best solution by iteratively improving a candidate solution in relation to a specific quality measure. PSO involves a swarm of particles moving through the solution space, with each particle representing a candidate solution. These particles modify their positions based on their own and their neighbors' experiences, using basic mathematical procedures. The method strikes a balance between exploration and exploitation by utilizing velocity updates that include cognitive (individual) and social (swarm) components, allowing particles to effectively settle on optimal or near-optimal solutions.

Integrating PSO with Fractional Order Proportional and Integral (FOPI) controllers yields a powerful hybrid technique known as PSO-FOPI. In this method, PSO is used to optimize the FOPI controller's settings, such as proportional gain, integral gain. PSO is especially useful for tweaking these parameters because of its capacity to effectively handle complex, non-linear, and multidimensional optimization problems. PSO-FOPI uses PSO's global search

capabilities to identify the best set of parameters for minimizing a given objective function, such as the integral of absolute error (IAE), integral of squared error (ISE), or other control system performance criteria. This strategy assures that the FOPI controller performs superiorly in terms of transient responsiveness. The PSO-FOPI methodology has various advantages over standard tuning methods. First, it reduces the need for human tweaking, which can be time-consuming and ineffective in complicated systems. Instead, PSO automates the optimization process, guaranteeing that the controller parameters are fine-tuned for peak performance. Second, the hybrid PSO-FOPI approach is extremely versatile and may be used in a variety of control systems, including power systems, robotic systems, and industrial automation processes. The ability to optimize fractional orders enables more precise control and management of systems with long memory and hereditary features. PSO-FOPI can also be used in real-time applications, because to advances in computer power and digital signal processing. Figure 3.13, shows the PSO-FOPI flow diagram.

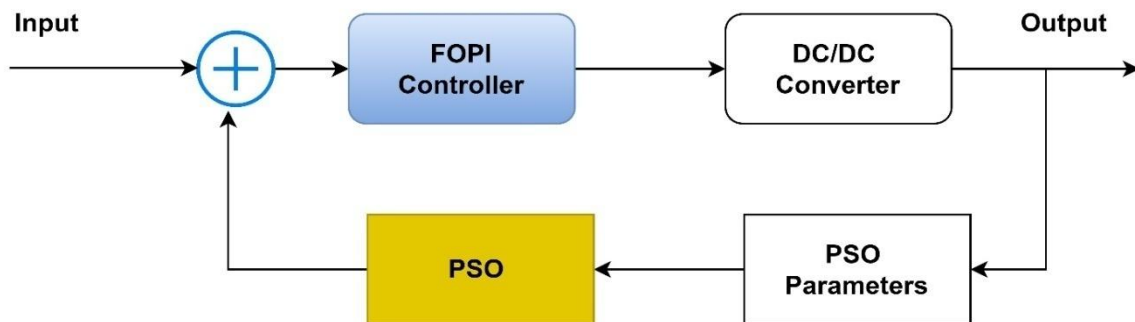


Figure 3.13 PSO-FOPI block set

Particle Swarm Optimisation (PSO) is utilised in this challenge to minimise ripple content, minimize peak overshoot, and maintain steady output under varying load conditions by appropriately adjusting the duty cycle. A set of PID controller gains is represented by each

"particle" in the PSO swarm, and the algorithm iteratively modifies these values according to how well they regulate the output voltage. The PSO is guided to look for parameter combinations that minimise the error between the desired and actual output voltages by the fitness function, which is often defined as a measure of this error.

3.4.5 Genetic Algorithm (GA) and GA-Based FOPI (GA-FOPI) controller

The genetic algorithm, or GA, is a popular technique for resolving multivariate optimisation issues. It is a fairly intricate algorithm that is seen as challenging by those who utilise traditional genetic logic-based optimisation techniques. GA uses an evolutionary algorithm to optimise functions by modelling biological processes. In biology, the combined set of parameters is called a chromosome, and GA parameters stand in for genes. In the solution space, each chromosome has a fitness value and is encoded using binary or decimal number sequences. Under specific guidelines, the population's fitness is maximised or minimised. The surviving sequences that are randomly modified by information changes combine to generate each new generation. First, the copying procedure is carried out in accordance with the population's observed chromosomal performance when GA is implemented. Because of this, better chromosomes are more likely to make copies and to contribute to the new population. Genetic operators like crossover and mutation are then used by GA to generate a new population in each generation. The population has members who are more fit after a few generations. Proliferation, crossover, and mutation operators are used, fitness is calculated, and coding solutions are all part of GA. A randomly generated population of chromosomes that may hold the key to solving the problem is used by GA to begin the optimisation process. In GA, the parameters, restrictions, and objective function are defined, just like in other optimisation techniques. Similar convergence checks are made at the algorithm's conclusion.

DC-DC converters are controlled in this study using traditional PI and FOPI (PI^λ) techniques. Specifically, the parameters for PI and FOPI (PI^λ) are optimised with values of (K_p , K_i) and (K_p , K_i , and λ). The GA approach was chosen in this study to optimise the parameters. Figure 3.14, shows the GA based FOPI, although similar to PSO but approach is different.

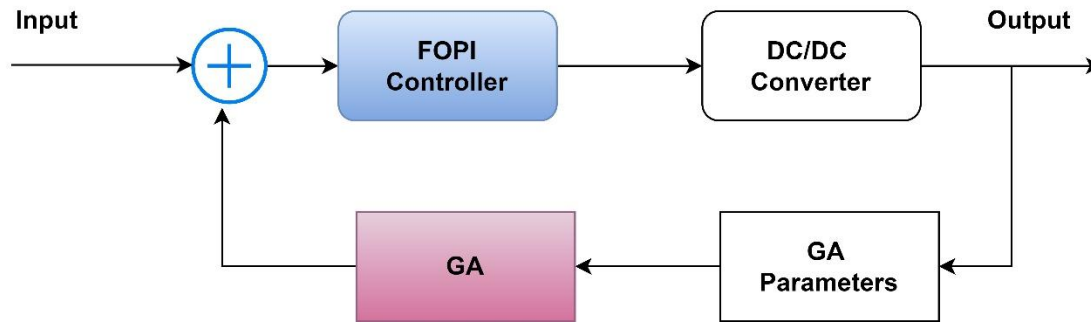


Figure 3.14 GA-FOPI structure

3.5 Mathematical modelling of GWO for PEMFC

Grey Wolf Optimization (GWO) is a nature-inspired optimization algorithm created by Mirjalili (2014) and based on the social hierarchy and hunting behaviour of grey wolves in the wild. GWO is a population-based metaheuristic that optimizes tasks by simulating grey wolf leadership and hunting mechanisms. The method divides the population of solutions (wolf) into four categories: alpha (best solution), beta (second best), delta (third best), and omega (the rest of the population). These groups work together to encircle, hunt, and attack animals, resulting in optimal solutions in the search space. GWO has been used successfully to solve a variety of optimization problems due to its simplicity, flexibility, and efficacy.

Figure 3.14, shows the Grey wolf optimization for the FOPI values. The prey is the optimal value and the wolves follow the minimum path for optimal solution.

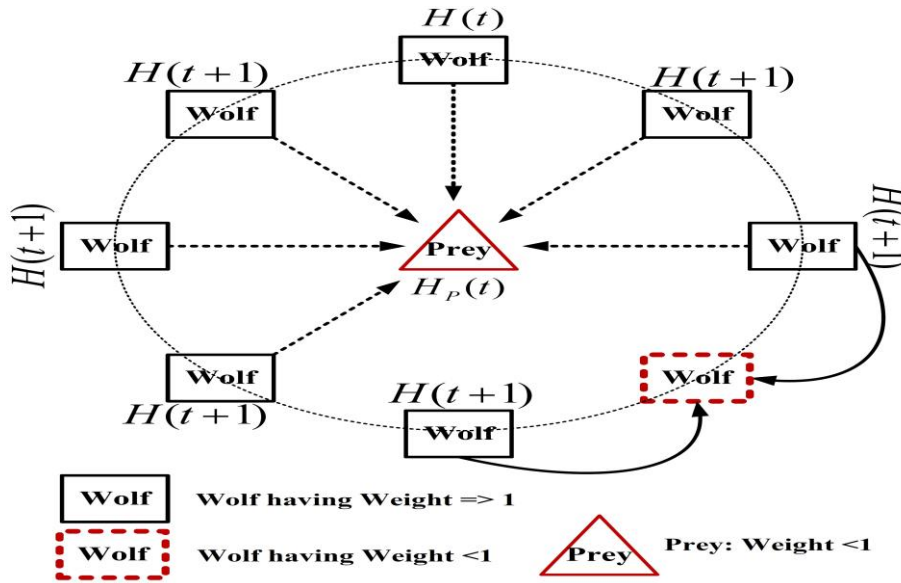


Figure 3.15 Grey wolf optimization for FOPI

For tuning the FOPI parameters, the grey wolf optimization uses the optimal solution using equation:

$$\vec{N}(t+1)^{n_z(t+1)-n_m(t+1)} = \vec{N}_p(t) + \vec{V}_A * \vec{V}_D \quad (3.75)$$

Here t represents number of iterations, \vec{N}_p is the required best solution, \vec{V}_A is co-efficient vector, n_z is total number of sensors parameters monitored, n_m is number of parameters away from optimal solution, and \vec{N} is highly trusted node. In equation 3.76, \vec{V}_D can be defined as follows:

$$\vec{V}_D = |\vec{C} * H_p(t) - \vec{H}(t)| \quad (3.76)$$

Vectors \vec{V}_A and \vec{C} can be calculated using equation 3.77 and 3.78.

$$\vec{V}_A = 2\vec{V}_A * \vec{r} - \vec{a} \quad (3.77)$$

$$\vec{C} = 2\vec{r}_2 \tag{3.78}$$

Where, for each iteration, the component of r and r_2 linearly decreases from 2 to 0, and are random vectors in the range [0, 1]. The GWO approach uses alpha, beta, and delta decisions to produce the best possible results. After each iteration, the position is updated and utilized to choose the optimal solution. Similarly, figure 3.16, shows the DC/DC converter model made in MATLAB. Flow chart for the methodology is shown in the figure 3.17. By appropriately adjusting the switching frequency, grey wolf optimisation (GWO) is utilised in this challenge to minimize peak overshoot, reduce ripple content, and maintain steady output under varying load conditions.

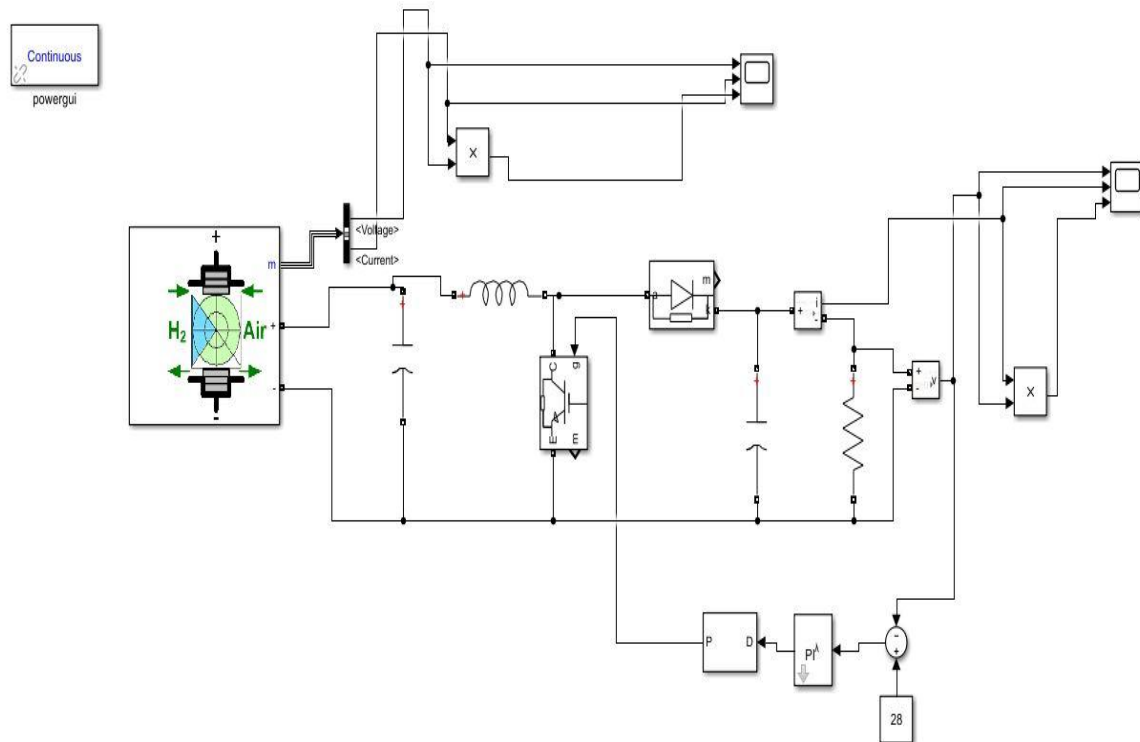


Figure 3.16 DC/DC boost converter design for PEM Fuel cell

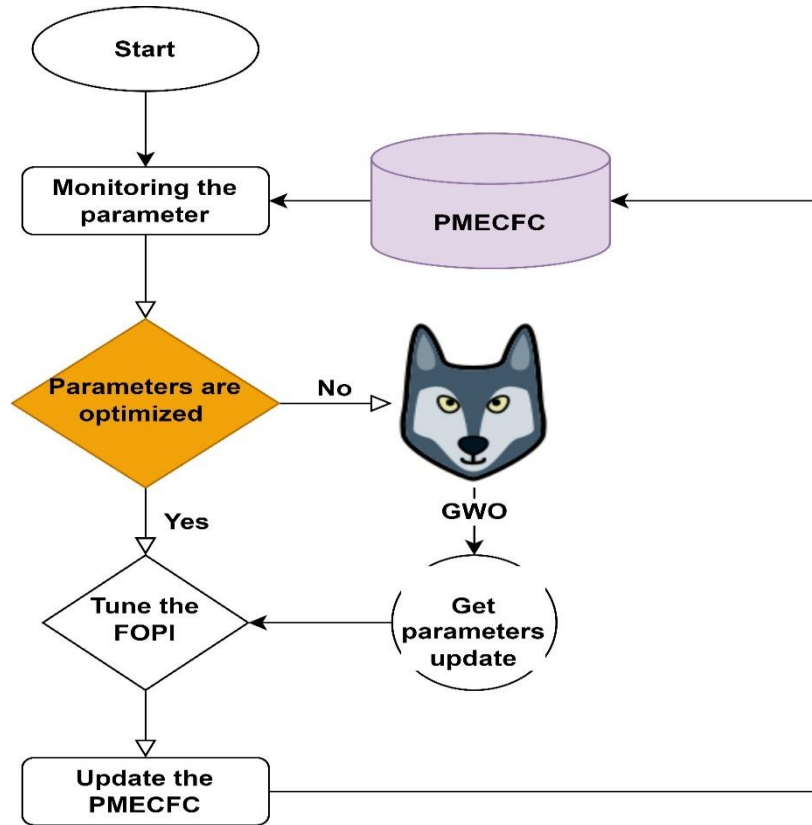


Figure 3.17 Complete flowchart of methodology

Proton Exchange Membrane Fuel Cell (PEMFC) mathematical modelling is an important field of study with great potential to improve fuel cell performance, stability, and efficiency. PEMFCs are a potential renewable energy technology, but they face several difficulties due to their sensitive to changing operating conditions and intricate, nonlinear dynamics. Advanced control strategies that can precisely simulate and govern PEMFC activity are needed to address these problems. The research and methods included in this article show how fractional-order controllers and optimization algorithms work together to manage these complexity in an efficient manner, improving PEMFC system performance.

The transition from conventional integer-order models to fractional-order dynamic models is one of the major developments in PEMFC control. The PEMFC's complicated activity is better represented by the fractional-order method, especially when it comes to expressing the system's genetic characteristics and memory effects. Even though they work well in many situations, traditional integer-order models frequently struggle to capture the complex dynamics of PEMFCs, particularly when there are fluctuations in load and disturbances.

In conclusion, research into the mathematical modelling and control of PEMFC systems is essential and will have a big impact on clean energy technology in the future. One effective way to overcome the difficulties involved in PEMFC functioning is to combine optimization algorithms, sophisticated control techniques like FOPID controllers, and fractional-order dynamic models. The study's findings show that these cutting-edge methods have the potential to greatly improve the efficiency, stability, and performance of PEMFC systems, opening the door for a wider range of applications. In the chapter 4, the results and discussion is reported for the developed model and summarized its output response for the application in PEMFC.

CHAPTER 4

RESULT AND

DISCUSSION USING

THE SIMULATION

RESULTS

Chapter 4: Results and Discussion

The study of proton exchange membrane fuel cells (PEMFCs) has brought to light the significance of sophisticated control techniques for raising the systems' dependability and efficiency. PEMFCs are acknowledged for their potential in the production of clean energy, but their intricate, nonlinear dynamics pose several difficulties. Because of these difficulties, complex mathematical models and control strategies that accurately represent PEMFC behaviour under a range of operating situations must be developed.

This section explores the findings and analysis from applying optimization algorithms in conjunction with fractional-order control techniques on PEMFC systems. In contrast to conventional integer-order models, fractional-order dynamic models provide a more accurate depiction of PEMFC behaviour. This is the main emphasis of the research. Furthermore, the thesis assesses the effectiveness of Fractional PID (FOPID) controllers that have been tuned using Grey Wolf Optimization (GWO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA).

The discussion and results are arranged so that the performance analysis of the FOPID controllers is presented after the results of the fractional-order dynamic modelling. After that, the section looks at how various optimization strategies affect controller performance and compares GA, PSO, and GWO in relation to PEMFC control. Ultimately, the discourse delves into the wider ramifications of these discoveries, taking into account the obstacles and prospective paths for further investigation within this domain.

4.1 Simulation of fractional order plant with and without FOPID

In order to check and verify the model stated in the above section MATLAB software is used to simulate the results and compare with the exiting methods.

The optimal control approaches previously presented enable smooth regulation of the supply manifold pressure in the PEM fuel cell system. We chose three different control mechanisms to effectively execute these schemes for the complex process of managing PEM fuel cells.

Create a fourth-order PEMFC model in section 3.1.2, taking into account the compressor's angular speed, supply heat exchanger, partial pressure of nitrogen, and partial pressure of oxygen as state variables. Based on the given table 4.1 generate the state space model which is already describe in modelling section.

Table 4.1 Simulation parameters of PEMFC system

Parameter	Symbol	SI units	Value
Atmospheric pressure	P_{atm}	Pa	101,325
Saturation pressure	P_{sat}	Pa	3140.4
Average ambient air relative humidity	Θ_{atm}	--	0.5
Atmospheric temperature	K	T_{atm}	298.15
Air-specific heat ratio	G	--	1.4
Stack temperature	T_{st}	K	353.15
Specific heat of air	C_p	J/kg/K	1004
Universal gas constant	R	J/mol/K	8.31451
Molar mass of oxygen	MO_2	kg/mol	32×10^{-3}
Molar mass of nitrogen	MN_2	kg/mol	28×10^{-3}

Molar mass of vapour	M_v	kg/mol	28×10^{-3}
Molar mass of air	$M_{a, atm}$	kg/mol	29×10^{-3}
Cathode volume	V_{ca}	M^3	0.01
Supply manifold volume	V_{sm}	M^3	0.02
Compressor motor mechanical efficiency	η_{cp}	%	0.8
Compressor efficiency	h_{cm}	%	0.98
Compressor and motor inertia	J_{cp}	N.m	5×10^{-5}
Compressor motor resistance	R_{cm}	ohm	0.82
Motor constant	K_v	V/ (rad/sec)	0.0153
Cathode outlet throttle discharge coefficient	C_D	---	0.0124
Cathode outlet throttle area	A_T	M^2	0.002
Number of cells in fuel cell stack	n	---	381
Oxygen mole fraction	$y_{O_2, atm}$	----	0.21
Motor constant	K_t	Nm/A	0.0153

The state space parameter of the corresponding PEMFC model is developed using the simulation parameters as mentioned in table 4.1 which is shown as below:

$$A = \begin{bmatrix} -10.85 & -7.671 & 0 & 7.65 \\ -28.69 & -32.32 & 0 & 28.94 \\ 0 & 0 & -7.329 & -0.040 \\ 19.84 & 19.84 & 89.95 & -2147 \end{bmatrix} \quad (4.1)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 365.7 \\ 0 \end{bmatrix} \quad (4.2)$$

$$C = [0 \ 0 \ 0 \ 1] \quad (4.3)$$

To design fraction controller utilising Chen approach usually require a first order time delay system. That why utilising model order reduction technique generate a FOPTD for the relevant 4th order system. The FOPTD transfer model is given below:

$$G(s) = e^{-0.0955s} \frac{2821.3}{s + 2.375} \quad (4.4)$$

Case study 1: Typical proportional integral controller (PI)

In this section the process model is integer order and controller is well spread PI controller tuned by SIMC technique.

Case study 2: Non-Integer order PI controller for FOPTD system

In this section the process model is integer order and controller is FPI controller, featuring two additional tuning parameters, offers enhanced control abilities, tuned by Chen method.

Case study 3: Non-integer order plant with a Non-Integer PI controller

The ultimate method is to employ a fractional controller (FPI) that is adapted to the specific identified non-integer order process model.

The plant parameters for each controller are displayed in Table 4.2. Table 4.3 displays the various steady-state and transient responses of the controller, including peak overshoot, settling time, and rising time. Integral absolute error (IAE) and integral square error (ISE) minimization are used in Table 4.4 to display the controller performance. For a fractional order model, the optimal performance is obtained with a fractional controller.

Set-point tracking is an indicator to evaluate controller performance. In the context of the fuel cell, supply manifold pressure is set to 2.2 Pa. Testing the controller's performance reveals considerable improvements in Integral Square Error (ISE), Integral Absolute Error (IAE), and other closed-loop response characteristics. The paper compares the PI controller to two other control approaches: the FPI controller and the FMFPI controller.

When compared to the PI controller, the ISE results show a 5.75% improvement in FPI and a 68.35% improvement in FMFPI. Furthermore, the FMFPI technique cuts IAE by 51.80%, but the FPI control scheme elevates it by 29.05% when compared to the PI controller.

Analysing the closed-loop response of all developed controllers indicates considerable improvements in each one. When PI is compared to FPI and FMFPI control systems, the rising time improves by 50.30% and 71.75%, respectively, and the peak time improves by 59.74% and 77.13%. However, the setting time increases by 12% in the FPI scheme while decreasing by 48% in the FMFPI scheme. The improvement Percentage is showcased in table 4.4.

The closed-loop response elucidates how the controllers effectively control both servo and regulatory problems through set-point tracking and disturbance rejection, respectively. Figure

4.1 depicts the closed-loop performance of all designed controllers in controlling the supply manifold pressure at 2.2 Pa. Set-point tracking is employed in order to evaluate efficiency from the controller's viewpoint. For non-integer order plants with fractional controllers, the best set point tracking performance is achieved.

Table 4.2 Controller parameter for different plant

Plant	Controller	Parameter
Integer order plant $G(s) = e^{-0.0955s} \frac{2821.3}{s + 2.375}$.	PI Controller	$K_p=0.0019$
		$\tau_c=0.4200$
Integer order plant $G(s) = e^{-0.0955s} \frac{2821.3}{s + 2.375}$.	FPI Controller	$K_p=0.0014$
		$K_i=0.007038$
		$\lambda=0.9$
Fractional order plant $G(s) = \frac{1}{0.00038353s^{1.1854} + 0.00087687s^{0.0086269}}$	FPI Controller	$K_p=0.0014$
		$K_i=0.016364$
		$\lambda=1.1899$

Table 4.3 Transient response for different controller used for this study

Type of Controller	Rise time(sec)	Peak overshoot (%)	Peak time(sec)	Settling time (sec)
PI	0.4751	2.2	0.6263	0.825
FPI	0.2361	2.75	0.2521	0.924
FMFPI	0.1342	2.81	0.1432	0.425

Table 4.4 Performance metric of different controller

Type of Controller	ISE	IAE
PI	8.03×10^{-1}	4.756×10^{-1}
FPI	7.568×10^{-1}	6.138×10^{-1}
FMFPI	2.541×10^{-1}	2.292×10^{-1}

Table 4.5 Improvement percentage of performance metric in different control scheme

Controller performance	% improvement in FPI over PI	% improvement in FM-FPI over PI
Rise time(sec)	50.30	71.75
Peak time(sec)	59.74	77.13
Settling time(sec)	- 12.00	48
ISE	5.75	68.35
IAE	-29.05	51.80

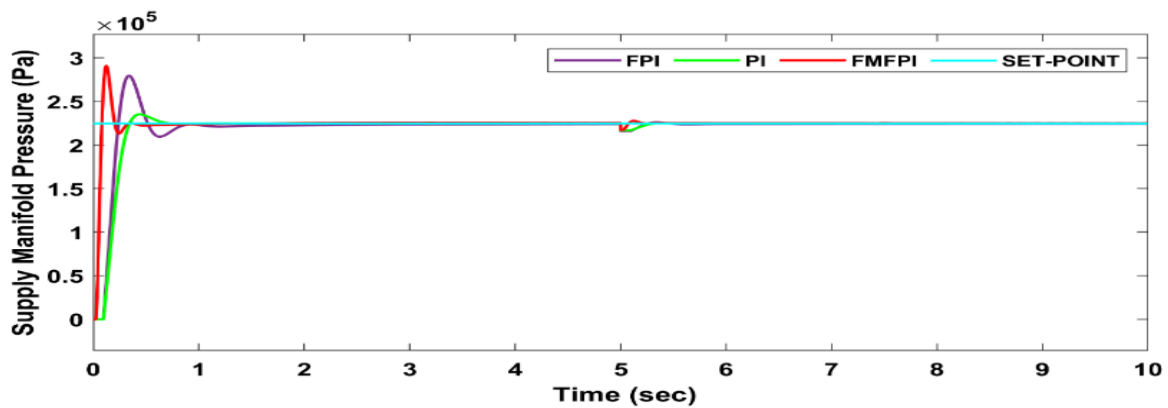


Figure 4.1 Supply manifold pressure comparison for different cases

4.2 Simulation of GA based FOPID for PEMFC

To model the 7th PEMFC for our research work, the modelling parameter is taken from the reference, which is described in the table 4.6. With the help of realistic data in the table 4.6, the model is modelled accurately.

Table 4.6 PEMFC parameters (Park 2014)

Parameters	Values
Gas constant	0.082 [L atm/mol/K]
Number of cells	35
Operating temperature	353 K
Cathode volume	0.010 m ³
Anode volume	0.005 m ³
Oxygen reactant factor	0.209
Hydrogen reactant factor	0.999
Nitrogen reactant factor	0.780
Hydrogen inlet flow rate	0.061 L/s
Water flow rate	0.0019 L/s
Oxygen inlet flow rate	4.540 L/s
Nitrogen inlet flow rate	0.150 L/s
Cell current density	100 A/m ²

It has been found that the linearised fuel cell model in consideration has a distinct equilibrium point, as indicated by the realistic numerical data shown in Table 4.6 given by

$$\tilde{x} = [0.5432 \quad 0.4216 \quad 2.0632 \quad 0.00021 \quad 6.4226 \quad 25.78944 \quad 0.4526]^T$$

The matrix used for linearizing the PEMFC model having values as stated in the table 4.7

Table 4.7 Matrix value for linearizing the PEMFC

Matrix J		Matrix K		Matrix L	
J11	-0.016	K31	0.0001	K11	8.6369e-08
J31	-0.0146	K41	1.1729	K12	4.318e-08
J41	-59.903	K52	0.0031	K13	-2.795e-06
J22	-0.0167	K62	0.0001	K14	-0.0244
J32	362.497	K72	-0.0164	K15	-0.0048
J42	-422.4421			K16	-6.390e-04
J53	-749.836			K17	-0.0006
J63	740.0775				
J73	2.9992				
J54	197.991				
J64	-207.767				
J74	2.999				
J55	197.991				
J65	740.077				
J75	-945.019				

The corresponding linearized system is

$$= \begin{bmatrix} -0.0167 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.0167 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.03640 & 0311.362 & 0 & 0 & 0 \\ 0 & 0 & -59.911 & -371.309 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -749.2712 & 197.8407 & 197.8407 \\ 0 & 0 & 0 & 0 & -740.0771 & -207.7676 & 740.0771 \\ 0 & 0 & 0 & 0 & 3.0520 & 3.0520 & -949.9757 \end{bmatrix} \partial_x(t) + \begin{bmatrix} 4.31*10^{-8} & 0 \\ 8.62*10^{-8} & 0 \\ 1.37*10^{-4} & 0 \\ 1.1729 & 0 \\ 0 & 3.1157*10^{-3} \\ 0 & -2.2625*10^{-15} \\ 0 & -1.181*10^{-2} \end{bmatrix} \partial u(t)$$

$$+ \begin{bmatrix} -1.462*10^{-3} \\ -2.82*10^{-3} \\ -2.847*10^{-6} \\ -2.4372*10^{-2} \\ -4.8209*10^{-3} \\ 0 \\ 1.8285*10^{-2} \end{bmatrix} \partial f_c(t)$$

The Eigen values of a matrix are negative that implies all the poles are placed left side of the S plane, means open loop system is asymptotically stable. Also check the rank of the matrix which is equal to the order of the system. It basically indicates the system is controllable as well as observable. Initially look at the open loop response for hydrogen and oxygen pressure since they are the system output variables. Figure 4.3 basically show the open loop response for H₂ using Ziegler Nichols tuning method. The red line in the figure 4.3 indicates the slope and blue line indicates open loop process reaction curve. Figure 4.4 describe the zero input stability of all seven states. When the input is zero all the state are converge properly. Develop a GA-based PID controller, a GA-based FOPID controller, and a PID controller using the Zieger-Nichols tuning approach for this problem. In section 3.3 already discuss how to model this controller. The Genetic Algorithm (GA) is run through several iterations to achieve the best-fit fractional PID controller parameters (Kp, Ki, λ). In order to reduce performance metrics like the Integral of Squared Error (ISE) and Integral of Absolute Error (IAE), the algorithm evaluates and adjusts the parameter set at each iteration. Until the optimum controller gains are obtained (figure 4.5-figure 4.8) the convergence graphs show how the fitness value increases over iterations.

Figure 4.5 and 4.6 shows closed loop response of H₂ using GA based PID controller. Similarly Figure 4.7 and 4.8 shows closed loop response of O₂ pressure using GA based PID controller. Also, examine the closed-loop response of H₂ pressure (Figure 4.9) after the Zigler-Nichols tuning method has been applied to its PID controller.

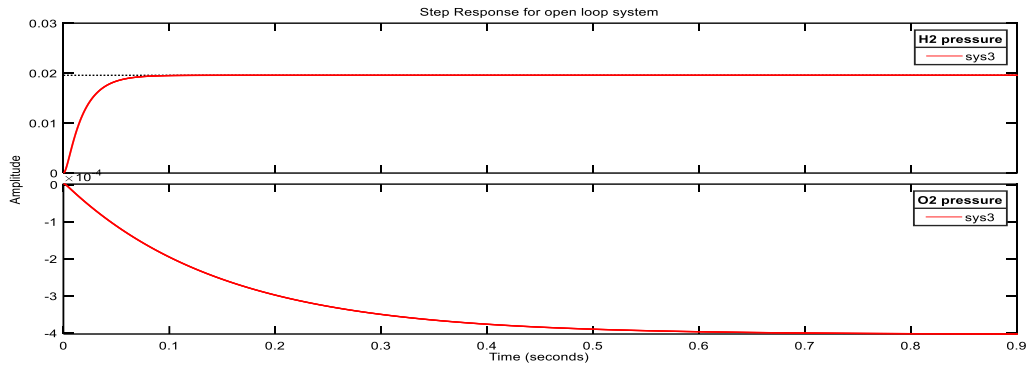


Figure 4.2. Open loop response for H₂ and O₂ pressure

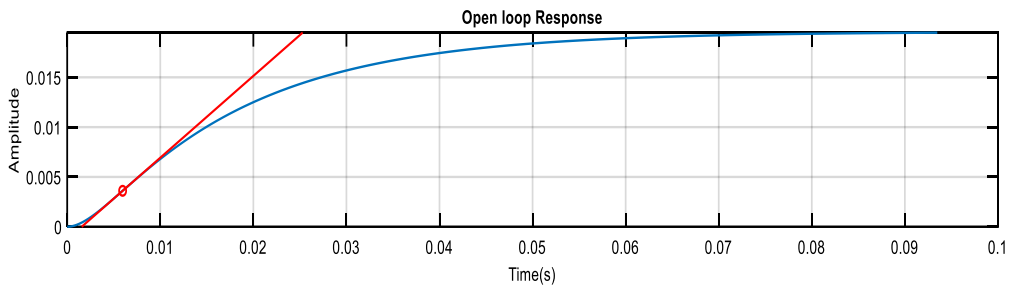


Figure 4.3 Ziegler Nichols open loop response for H₂ pressure

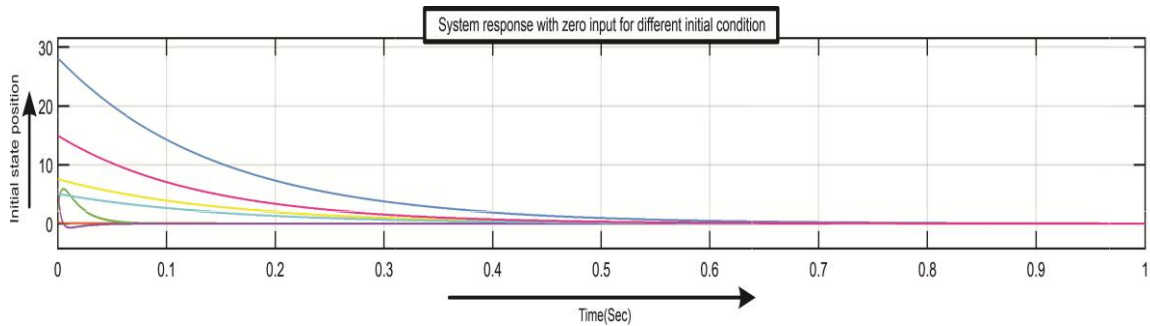


Figure 4.4 system state response with zero input

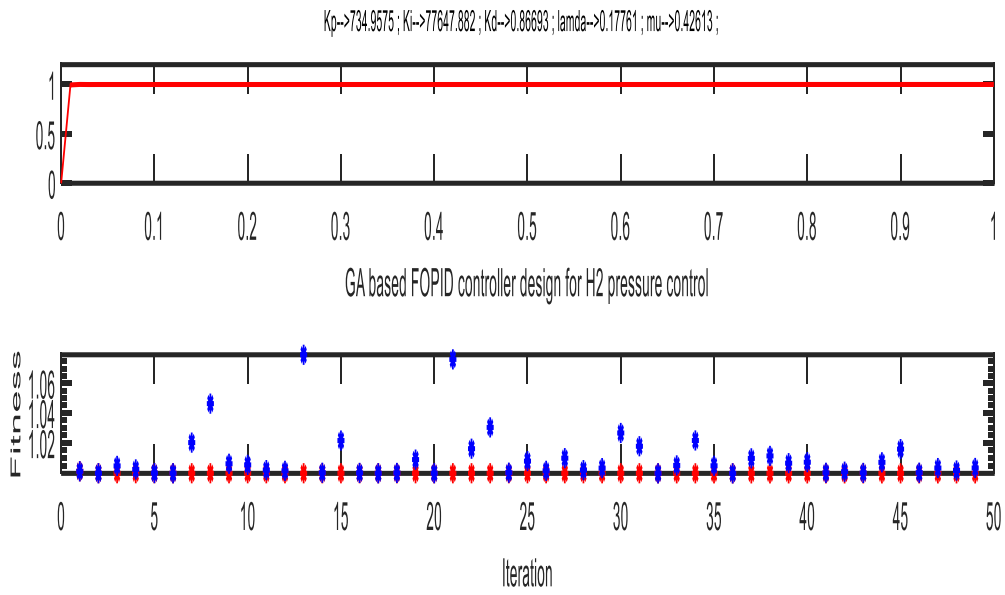


Figure 4.5 Closed loop response of H₂ pressure using GA based FOPID controller

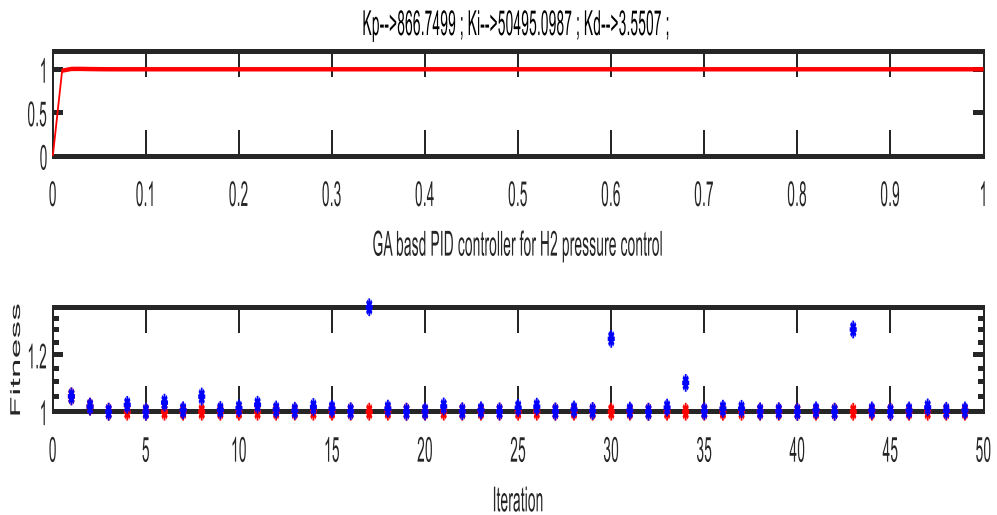


Figure 4.6 Closed loop response of H₂ pressure using GA based PID controller

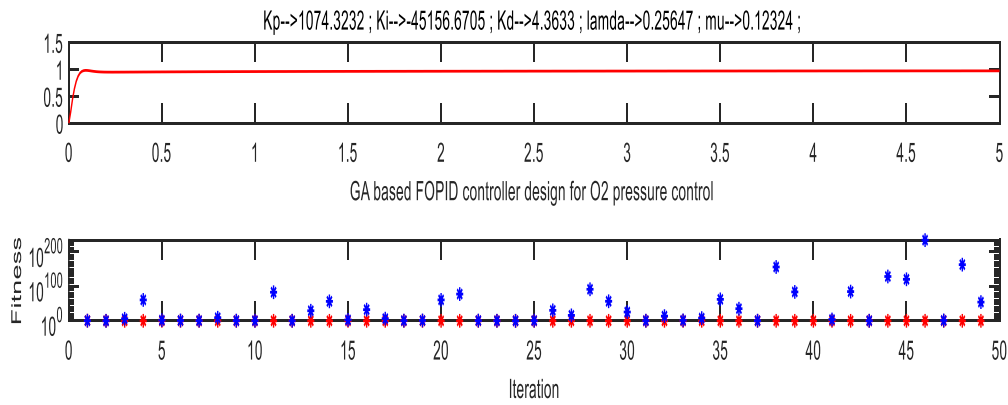


Figure 4.7 Closed loop response of O₂ pressure using GA based FOPID controller

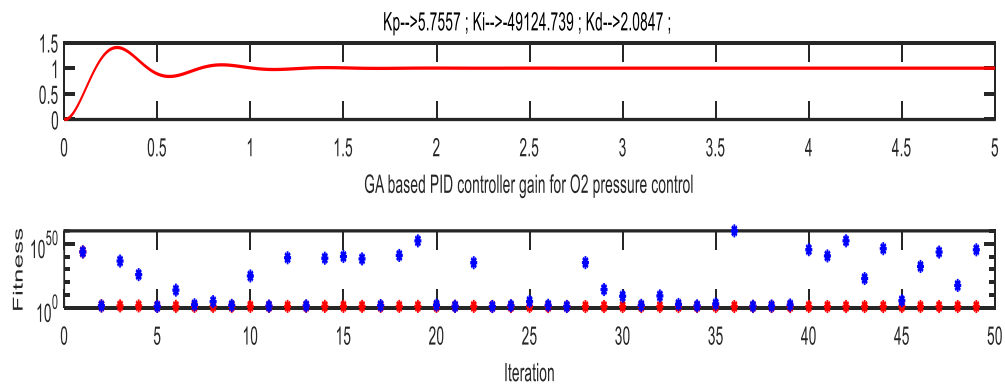


Figure 4.8 Closed loop response of O₂ pressure using GA based PID controller

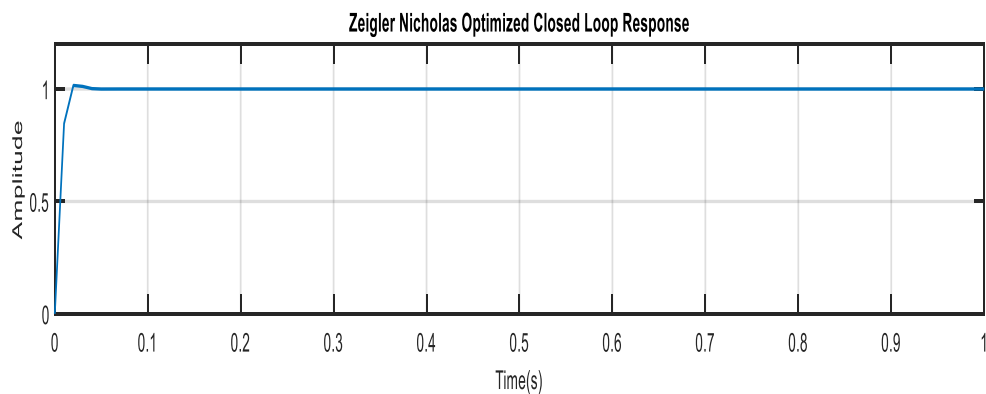


Figure 4.9 Ziegler Nichols closed loop response for H₂ pressure

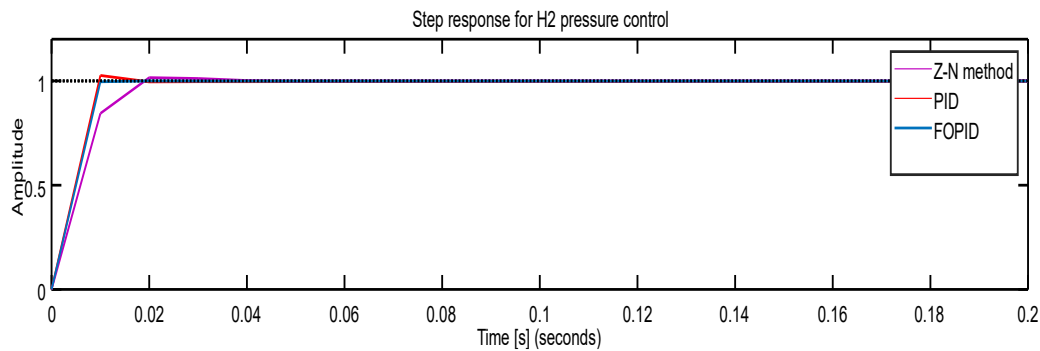


Figure 4.10 Step response of H₂ with Z-N method, PID and FOPID

Figure 4.10 illustrates the hydrogen (H₂) pressure control performance of three different controllers: the conventional Ziegler–Nichols (Z–N) tuned PID, the Genetic Algorithm (GA)–based PID, and the GA–optimized Fractional PID (FPID) controller. Among these, the GA–based FPID controller demonstrates the best dynamic response, exhibiting superior performance with reduced overshoot, faster settling, and smoother control action compared to the other two methods.

Figure 4.11 presents the oxygen (O₂) pressure control results, where only the GA–based PID and FPID controllers are considered. The Z–N tuned PID controller is excluded here, as its performance was already found inferior during the H₂ pressure control analysis. For O₂ control, the GA–based FPID again provides improved response characteristics — minimizing both overshoot and undershoot, and achieving a faster rise and settling time compared to the GA–PID controller.

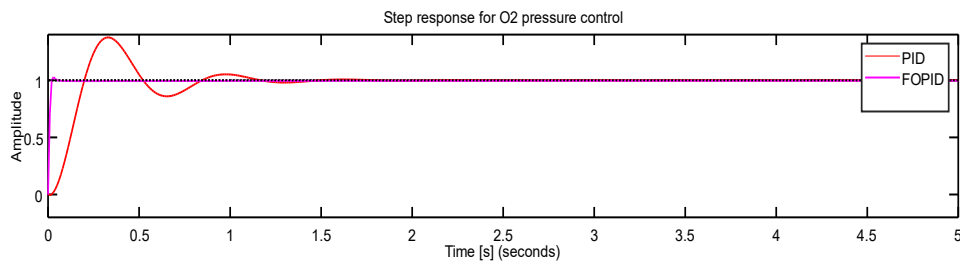


Figure 4.11 Step response of O₂ with PID and FOPID

Apart from the simulation result we used confusion matrix of 2x2 to obtain the accuracy, sensitivity and precision. Table 4.8, shows the value of the confusion matrix during the simulation. The result shows that the proposed GA based FPID have an accuracy of 97%.

Table 4.8 Confusion Matrix

N=100	Predicted No	Predicted Yes	Total of Row
Actual No	40	10	50
Actual Yes	4	46	50
Total of Column	44	56	-

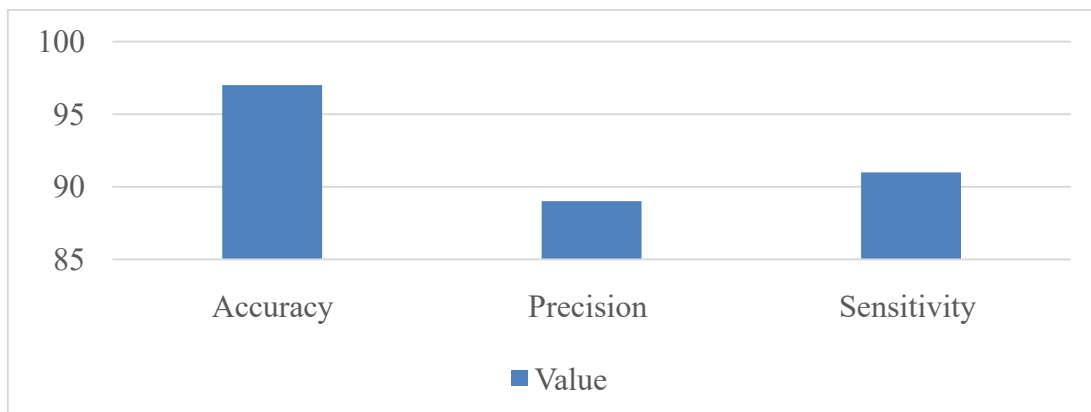


Figure 4.12 Proposed model parameter evaluation

4.3 Comparison with GA based PID and FOPID controller

The FOPID is an advance version of PID controller having two more parameters for tuning which help the system to improve its performance. Especially for the non-linear and dynamic systems the parameters integral order gain and derivative order gain help to attend the best possible results. Table 4.9 presents the dynamic performance comparison of Genetic Algorithm (GA)-based PID and GA-based Fractional Order PID (FOPID) controllers for hydrogen (H₂) and oxygen (O₂) pressure control in a PEM fuel cell system. The evaluation parameters include rise time, settling time, overshoot, undershoot, peak amplitude, and fitness value, which together indicate control efficiency, stability, and transient performance. For H₂ pressure control, both controllers exhibit fast responses with small rise and settling times. The GA-PID controller yields a rise time of 0.0079 s and settling time of 0.0097 s, while the GA-FOPID controller gives a similar rise and settling time (0.008 s and 0.0098 s). However, the overshoot is drastically reduced from 1.2632 (GA-PID) to 0.0594 (GA-FOPID), indicating smoother and more stable control. The peak amplitude is nearly ideal (≈ 1.0), confirming that the FOPID controller eliminates oscillations around the setpoint. The fitness value is slightly improved (1.001 vs. 1.000), showing that the FOPID tuning achieved an almost optimal balance between speed and accuracy. Overall, for H₂ pressure regulation, both controllers perform well, but the GA-FOPID shows superior damping and minimal overshoot, which translates to smoother control action and improved stability.

The O₂ pressure dynamics are slower and more nonlinear, hence the differences between controllers are more pronounced. The GA-PID controller produces a rise time of 0.127 s and settling time of 1.1086 s, while the GA-FOPID reduces the rise time to 0.0542 s, indicating a much faster response. Overshoot for GA-PID is extremely high (37.5891 amplitude units), demonstrating poor damping, whereas GA-FOPID completely eliminates overshoot and

undershoot. The fitness value also improves significantly from 12.416 (PID) to 4.036 (FOPID), reflecting better optimization performance and reduced integrated error. The FOPID's peak amplitude (0.9687) is close to unity, confirming accurate tracking without oscillation or steady-state error.

Thus, for O₂ control, the GA-FOPID controller outperforms the GA-PID in all aspects—achieving faster rise, no overshoot, and smoother convergence to the desired pressure. The data confirm that introducing fractional-order dynamics (λ , μ) into the GA optimization framework enhances control precision for the PEM fuel cell pressure subsystem. The GA-FOPID controller offers improved transient characteristics (faster rise and settling), eliminates overshoot and undershoot, and provides better fitness values, indicating lower error indices such as ISE or IAE. Hence, the fractional-order controller provides superior adaptability and robustness, particularly for nonlinear and coupled processes like O₂ and H₂ pressure regulation in PEM fuel cells.

Table 4.9 Comparison with GA based PID and FOPID controller

Parameters	GA with PID		GA with FOPID	
	H ₂ (PC*)	O ₂ (PC*)	H ₂ (PC*)	O ₂ (PC*)
Rise Time(s)	0.0079	0.1270	0.008	0.0542
Settling Time(s)	0.0097	1.1086	0.0098	1.1956
Settling Min(amplitude)	0.9982	0.8597	0.9957	0.9186
Settling Max(amplitude)	1.0126	1.3759	1.000	0.9687
Overshoot(amplitude)	1.2632	37.5891	0.0594	0
Undershoot(amplitude)	0	0.6346	0	0
Peak(amplitude)	1.0126	1.3759	0.020	0.9687
Fitness value	1.000	12.416	1.001	4.036
*Pressure Control (PC)				

4.4 DC/DC converter optimization using GWO

The use of grey wolf optimization (GWO) with fractional order proportional-Integral (FOPI) controllers has resulted in considerable increases in system performance across a variety of control tasks. The key benefit of utilizing GWO to tune FOPI controllers is its ability to effectively navigate the search area and locate optimal settings that improve the controller's responsiveness. The experimental results reveal that GWO-FOPI controllers outperform standard PI controllers and other optimization-based FOPI controllers in terms of transient response, steady-state error, and overall stability. For example, in simulations including

complicated non-linear systems, the GWO-FOPID controller consistently produced shorter settling times, reduced overshoot, and fewer steady-state errors than standard tuning methods.

Create two PEMFC models depending on the parameters listed in table 4.10. The output voltage from the PEMFC stack is 15 volts when 35 cells are taken into account. When there are seventy cells, the PEMFC's output voltage increase to 30 volts.

Table 4.10 PEMFC Parameters ((Park 2014)

Parameters	Values
Gas constant	0.082 [L atm/mol/K]
Number of cells	35
Operating temperature	353 K
Cathode volume	0.010 m ³
Anode volume	0.005 m ³
Oxygen reactant factor	0.209
Hydrogen reactant factor	0.999
Nitrogen reactant factor	0.780
Hydrogen inlet flow rate	0.061 L/s
Water flow rate	0.0019 L/s
Oxygen inlet flow rate	4.540 L/s
Nitrogen inlet flow rate	0.150 L/s
Cell current density	100 A/m ²

In figure 4.13 shows the fuel cell transient voltage, current and power without converter when 70 cells are connected.

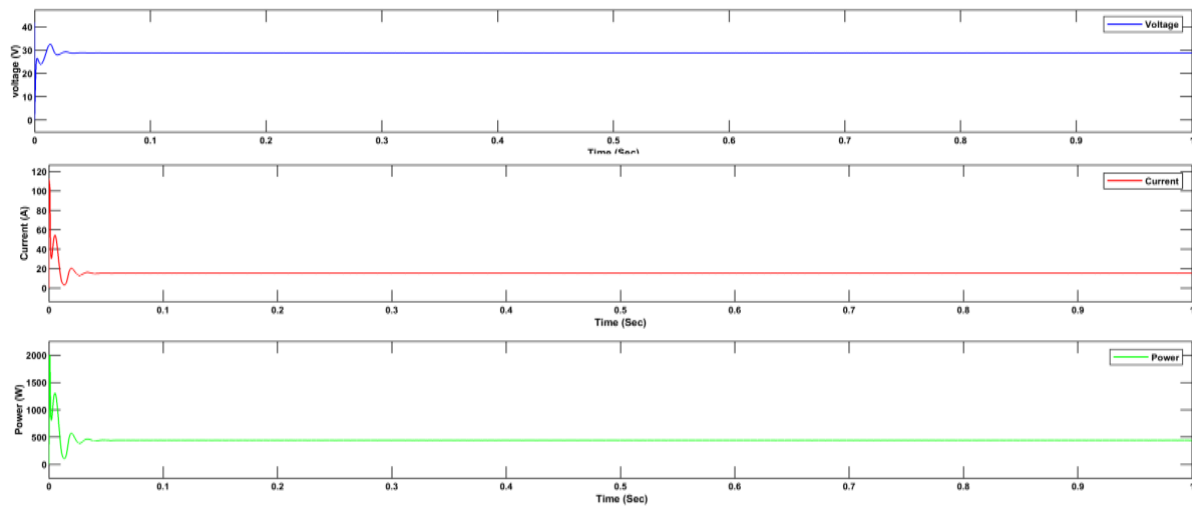


Figure 4.13 Fuel cell output current voltage and power transient response without converter

The goal of this work is to develop a dc-dc boost converter that keeps the voltage across the load constant. First, consider about the 15V PEMFC, which is coupled to a dc-dc boost converter. The output across the load should be set to 25 V. The DC-DC converter cannot maintain the desired voltage across the load when the PI controller is not correctly tuned. The outcome is shown in Figure 4.14. The PEMFC's output voltage is 15 volts, whereas the dc-dc converter's output is 20 volts.

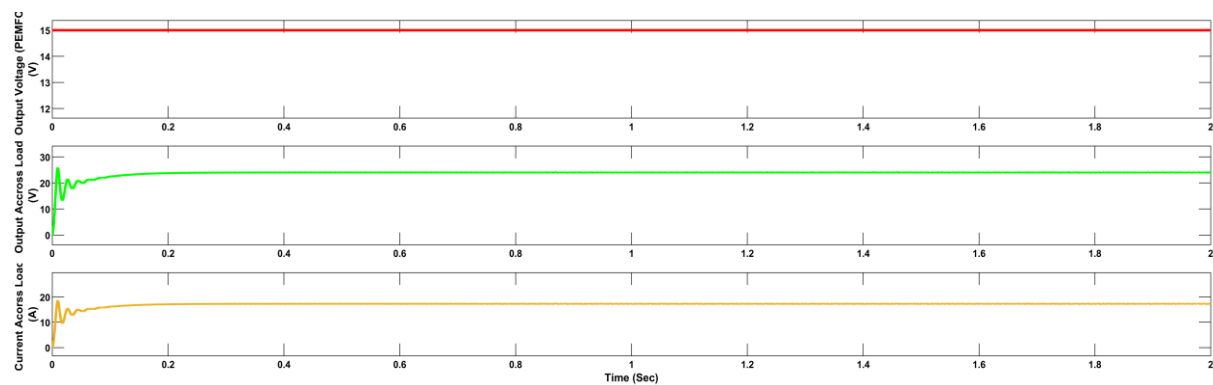


Figure 4.14 voltage and current across the load without adjusting the PI controller

Select a fractional controller with an additional parameter (λ) to help tweak the controller in order to address the issue. Tune the fractional PI controller using various optimisation techniques, such as GA, PSO, and GWO, to address the difficulty. The primary goal is to adjust the switching frequency so that the output voltage may be kept at 25 volts. The GWO-based dc-dc converter yielded the best result out of all the optimisation. Develop the fraction PI controller using the parameters and constraints listed in table 4.11. Figure 4.15 shows that the voltage across the load is 25 volts whereas the voltage from the PEMFC system is 15 volts.

Table 4.11 Design parameter and constrain considered for optimization

Parameter	value	parameter	value
Input volgae	15V	Range of inductor	(0.1 μ H-100 mH)
Output Voltage	25V	Range of capacitor	(0.1 μ F-100 μ F)
Output current	20 A	Switching frequency	(10 kHz-800 kHz)
On state resistance of MOSFET	6 m Ω	Reverse recovery charge in diode	50*10 ⁻⁹ A
Converter on time	10 ⁻⁵ sec	Percentage average of current	20% of I _O
Converter off time	10 ⁻⁵ sec	Percentage average of voltage	20% of V _O
Forward voltage drop on the diode	0.7V		

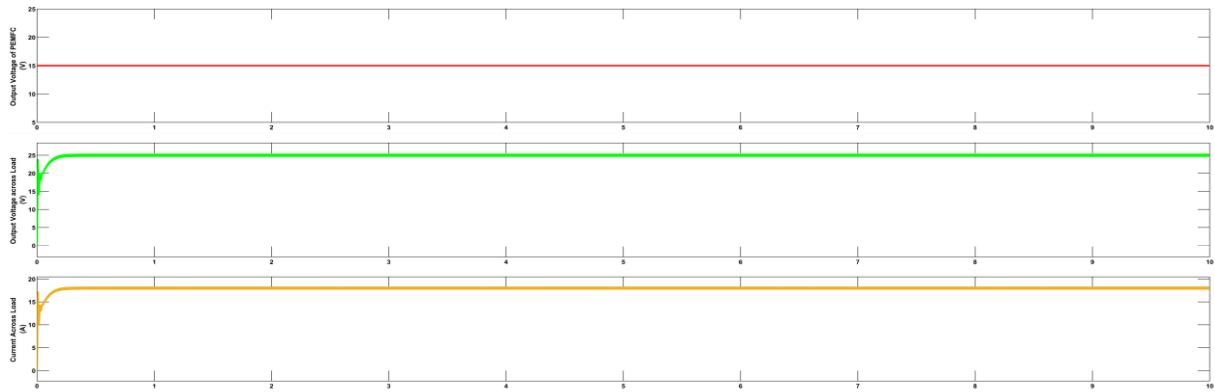


Figure 4.15 Voltage and current across the load using GWO based dc-dc converter

It's really challenging to keep the PEMFC voltage steady at all times. Temperature, oxygen pressure, and hydrogen pressure can cause the output to deviate from its specified range. For this reason, increase the PEMFC fuel cell's voltage in the Matlab model to observe how the output changes. In case of GWO based fractional controller provides best result compare to GA and PSO based controller. Figure 4.16 and 4.17 shows satisfactory results.

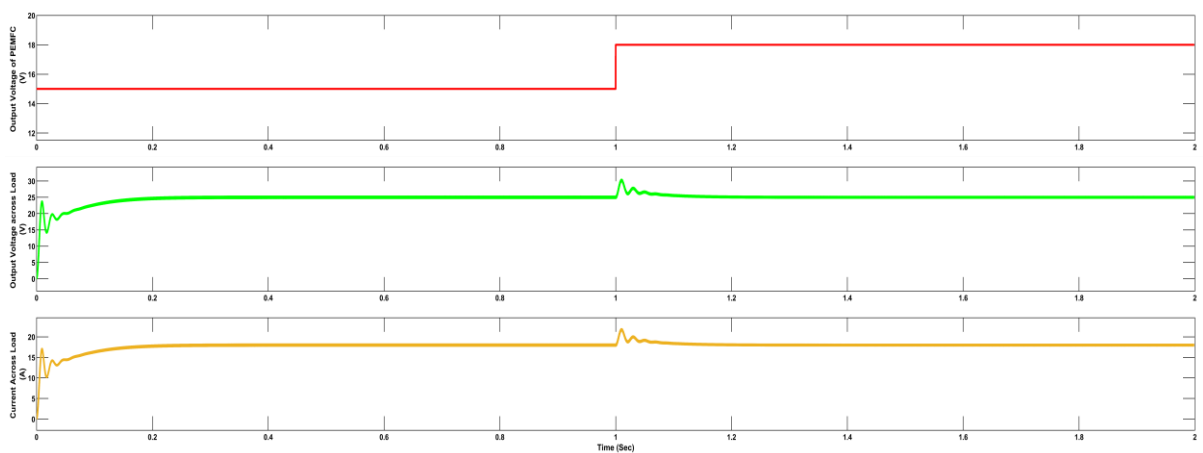


Figure 4.16 Output voltage and current due to change of voltage in PEMFC after 1 second

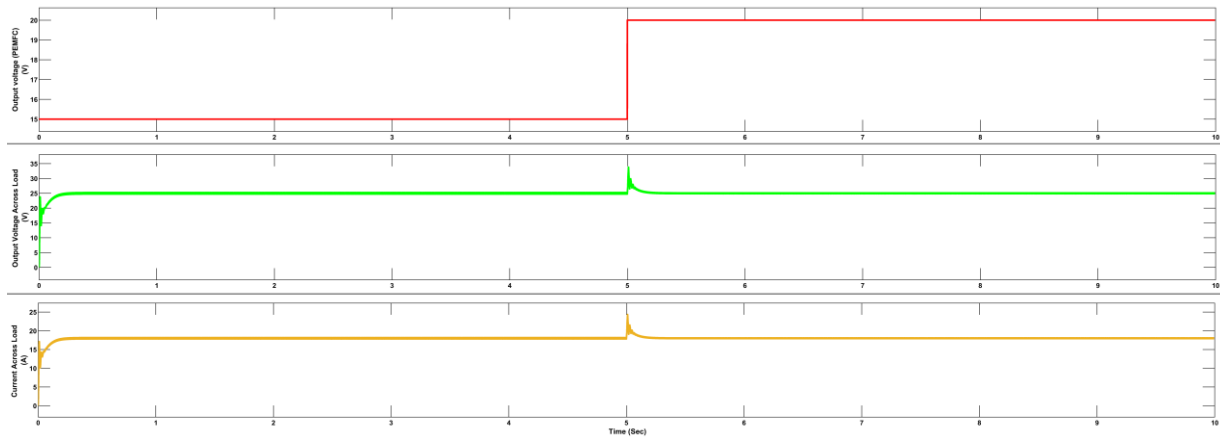


Figure 4.17 Output voltage and current due to change of voltage in PEMFC after 5 second

Figure 4.18 illustrates when a GWO-based fractional controller is used the ripple content inside the load voltage and current is very small. Basically it can able to maintain a constant voltage across the load.

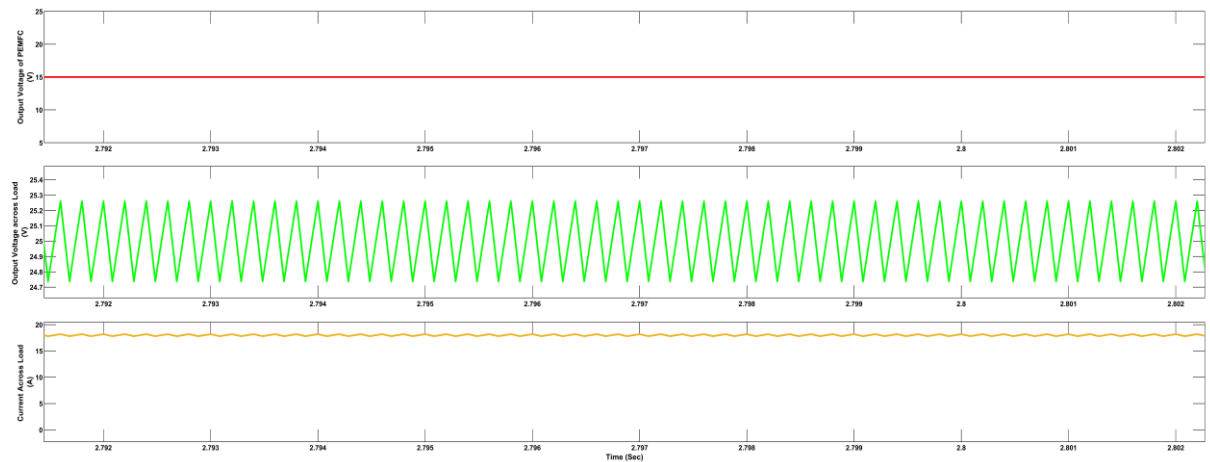


Figure 4.18 Ripple content in DC voltage and current across the load

Figure 4.19 consider 30 volt PEMFC and change the voltage at 10 sec. The minimum load change happen when use the GWO based fractional controller.

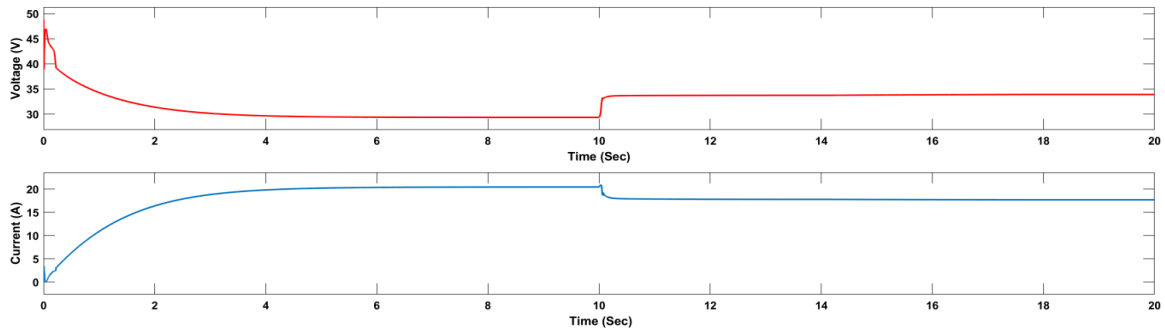


Figure 4.19 PEM fuel cell terminal voltage and current variation at 10 second

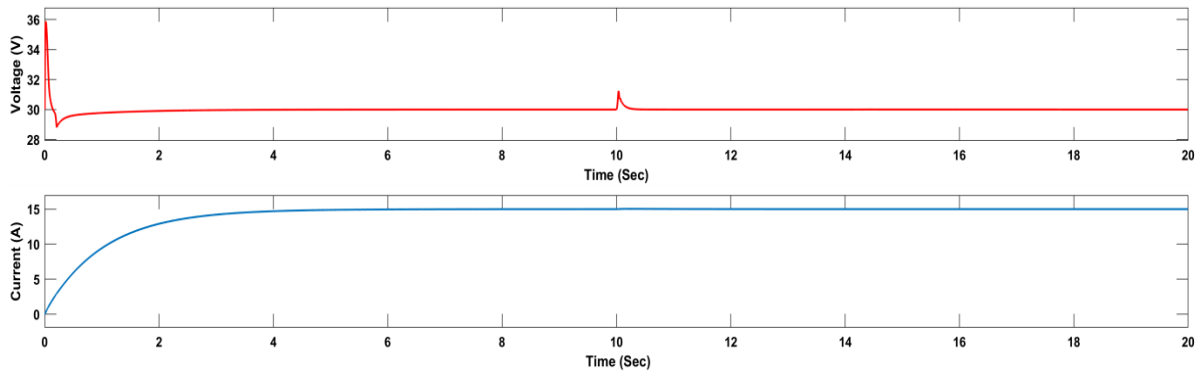


Figure 4.20 Converter terminal voltage and current using PSO-FOPID optimization in change in load

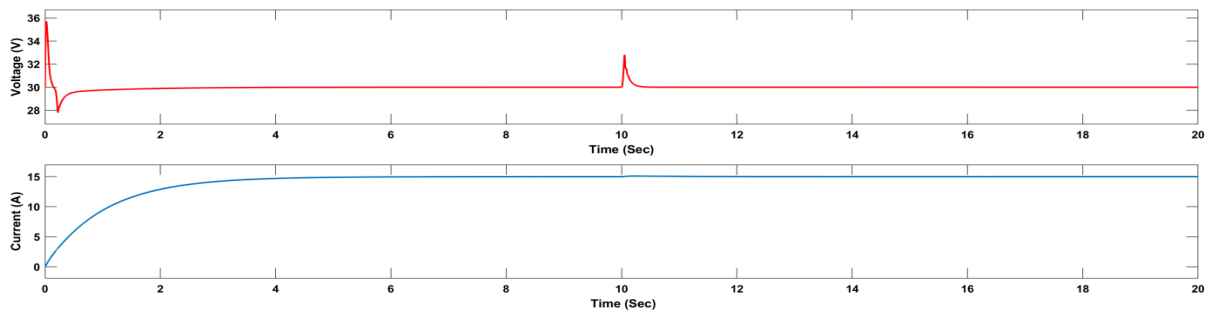


Figure 4.21 Converter terminal voltage and current using GA-FOPID optimization in change in load

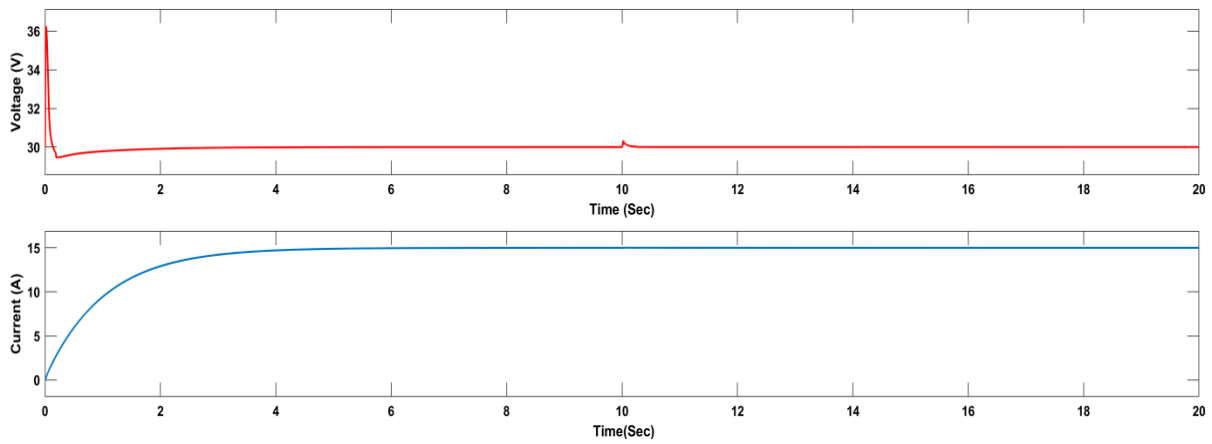


Figure 4.22 Converter terminal voltage and current using GWO-FOPID optimization in change in load

Figure 4.20 to 4.22, it is observed when the PEMFC voltage fluctuate, voltage across the DC-DC converter is also change. There is some oscillation at the load side. But result indicates that when optimize through GWO based fractional controller overshoot is minimum compare with GA and PSO based controller.

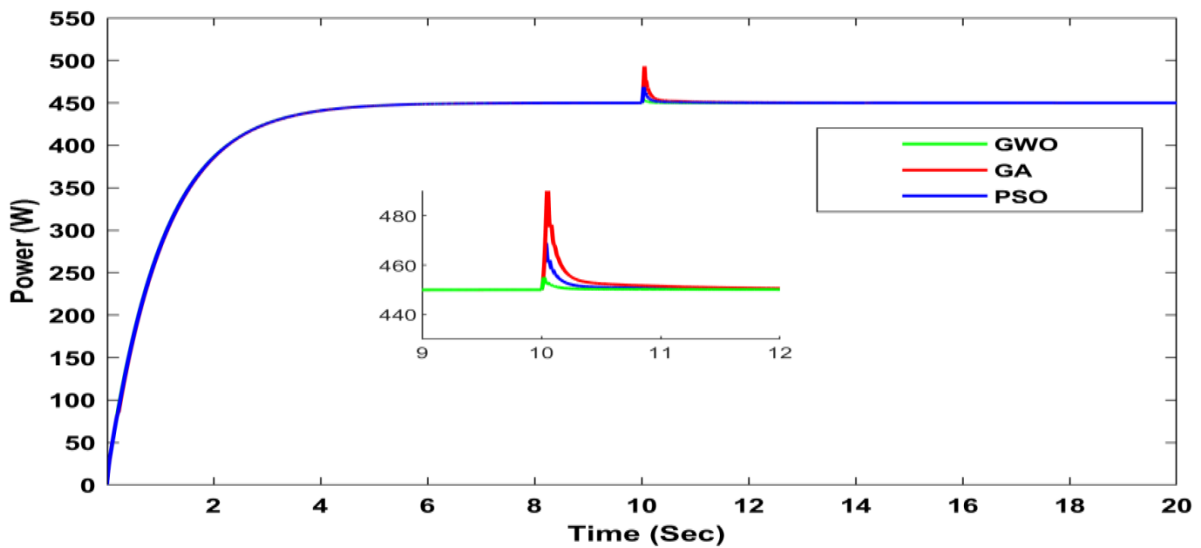


Figure 4.23 power fluctuation due to change in load

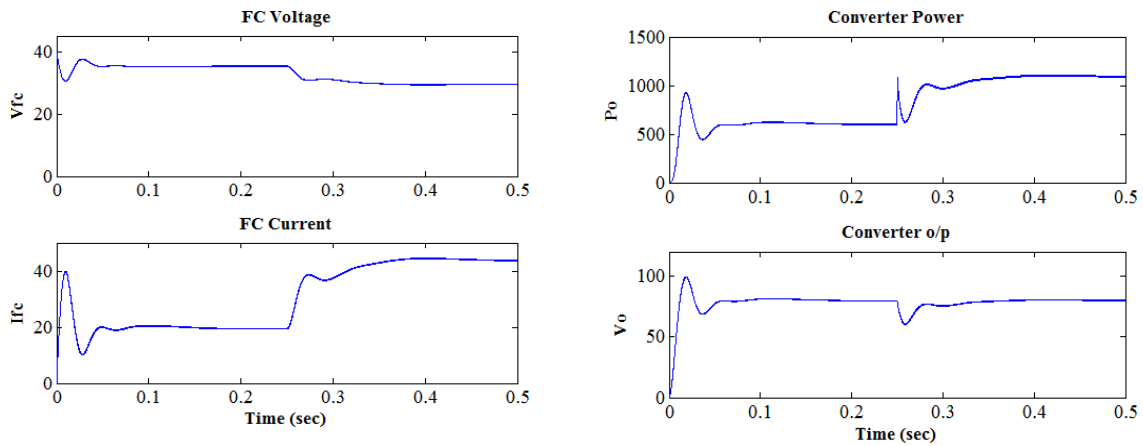


Figure 4.24 PEM fuel cell terminal voltage and current in change in load

In figure 4.24, it can be seen that when the voltage and current across the PEMFC change due to parametric variation, the voltage across the load which is connected across the dc-dc converter remain constant. Although there is some oscillation, when the voltage and current changes in PEMFC. The oscillation is very less when the fractional controller parameter (switching frequency) of dc-dc converter is optimized through GWO based optimization. Table 4.12 compares the tuned controller parameters Kp , Ki , and fractional order λ obtained using three different tuning methods—Conventional PI, Fractional Order PI (FOPI), and Grey Wolf Optimizer-based FOPI (GWO-FOPI)—for the PEM fuel-cell pressure-control loop. The table highlights how optimization strategy and controller structure affect tuning gains and fractional order. It serves as quantitative evidence that the GWO-based optimization significantly modifies the proportional and integral gains to achieve faster, more stable, and overshoot-free responses compared with the empirically or manually tuned controllers.

Table 4.12 Conventional PI & FOPI model values

Methodology	K _p	K _i	λ
Conventional PI	0.002	0.18	
FOPI	0.42	0.9	0.2
GWO-FOPI	0.73	0.56	0.01

Finally, the comparison of the proposed model is done with the existing models as shown in the table 4.13 Table 4.14, shows the performance metric for different controller.

Table 4.13 Comparison with the existing models

Parameters	GA-PI	PSO-PI	GWO-FOPI
Rise Time(sec)	0.4832	0.3251	0.1358
Settling Time(sec)	0.845	0.945	0.545
Peak Overshoot	2.25	2.7	2.85
Peak Time(sec)	0.636	0.2556	0.1552

Table 4.14 Performance metric comparison

Parameters	GA-PI	PSO-PI	GWO-FOPI
Fitness Function	78.2	80.5	90.8
ISE	0.845	0.7586	0.2442
IAE	0.4665	0.5372	0.3925

This study's simulations demonstrate that, in comparison to conventional PID controllers, the fractional PI/D controller dramatically lowers overshoot and settling time. This gain is especially noteworthy when dealing with disruptions like abrupt changes in load demand or fluctuations in the availability of hydrogen and oxygen. The value of using fractional-order control techniques in PEMFC applications is highlighted by the controller's capacity to adapt to these oscillations without sacrificing system efficiency or stability. The study also demonstrates the robustness of the controller, which keeps up excellent performance even under the various and erratic operating conditions that PEMFCs usually encounter. Because it was created using non-integer order dynamics, the fractional PI/D controller works especially well at controlling the complex flow and pressure characteristics of the PEMFC system. The simulation results show that this controller performs better than conventional integer-order PID controllers, especially when changeable input circumstances and fluctuating load currents are present. Maintaining ideal operating conditions in PEMFCs requires more adaptable and flexible regulation, which is made possible by the fractional PI/D controller's non-integer order dynamics.

The second section's results show that the GA-optimized fractional $PI^{\lambda}D^{\mu}$ controller performs better than non-optimized fractional controllers and conventional PID controllers. The process of optimization considerably improves the controller's capacity to sustain accurate pressure control in the face of disruptions and fluctuating operating circumstances. According to the simulations, the GA-optimized controller delivers reduced overshoot, enhanced stability, and shorter response times—all critical for PEMFCs to operate efficiently.

The influence of fractional-order dynamics on the PEMFC system's overall efficiency is one of the main conclusions drawn from the simulation findings. In addition to increasing pressure control, the GA-optimized fractional $PI^{\lambda}D^{\mu}$ controller helps the fuel cell operate

more efficiently, adding 2% to its overall efficiency. This efficiency boost is explained by the controller's capacity to keep the cathode side under ideal pressure circumstances, which reduces the possibility of flooding and guarantees that the fuel cell runs within its optimum parameters. The PEMFC's efficiency and dependability are further increased by its increased capacity to react rapidly to variations in load demand due to the decrease in overshoot and settling time.

Furthermore, a major development in control strategy design is the use of fractional-order controllers with optimization methods such as genetic algorithms. Through the application of optimization methods, the parameter space may be methodically explored in order to determine the best settings for the fractional-order controller, which guarantees that it is precisely calibrated to the unique dynamics of the PEMFC system. This method improves the performance of the controller and offers a framework for creating more sophisticated control schemes that may be used with other intricate nonlinear systems.

To sum up, these research' simulation results and discussion highlight the major benefits of adopting fractional-order controllers—especially ones that have been improved using genetic algorithms—for PEMFC system control. The improved stability, efficiency, and pressure control performance demonstrate how these sophisticated control techniques can be used to get around some of the problems that arise when operating PEMFCs. Adoption of such creative control measures will be critical to improving PEMFC technology research and commercialization as the need for clean and efficient energy solutions grows.

**CONCLUSION AND
FUTURE WORK**

5.1 Summary of findings

5.1.1 Key results and contributions of the research

The current study has investigated the complexities of employing fractional-order controllers to manage proton exchange membrane fuel cells (PEMFCs). It has been clear from the research that using fractional-order controllers provides a number of benefits over using conventional integer-order controllers, especially when it comes to controlling the intricate and nonlinear dynamics of PEMFCs. Fractional-order controllers, like the Fractional $PI^\lambda D^\mu$ (FOPID), perform better in terms of stability, response time, and overshoot—three important factors for PEMFC efficiency. The major findings of the study highlight the effectiveness of fractional-order controllers in preserving ideal pressure conditions at the cathode side of the PEMFC and boosting overall system efficiency.

The study also shown that fractional-order controllers perform noticeably better when optimization methods like Genetic Algorithms (GA) are used in their design and tuning. In a number of simulated cases, the GA-optimized fractional $PI^\lambda D^\mu$ controller performed better than both non-optimized fractional controllers and conventional PID controllers. The PEMFC's operational efficiency increased by 2% as a result of this modification, demonstrating the practicality of these sophisticated control techniques.

Additionally, the study aided in the creation of a fractional-order dynamic model for PEMFCs, which offered a more realistic depiction of the behaviour of the system under varied operating circumstances. The aforementioned model was helpful in the development and verification of the suggested control approaches, guaranteeing that the controllers were appropriately tailored to the distinct dynamics of the PEMFC system.

5.1.2 Effectiveness of fractional-Order controllers in optimizing PEMFC performance

The study's findings clearly demonstrate the value of fractional-order controllers in maximizing PEMFC performance. Specifically, the fractional $PI^\lambda D^\mu$ controller showed that it could precisely manage the pressure at the PEMFC cathode side even under varied operating conditions and disturbances. This degree of control is essential for avoiding flooding and preserving fuel cell efficiency, which is frequently lost in conventional control systems because of their incapacity to adequately manage the nonlinear dynamics of PEMFCs.

The implementation of fractional-order controllers resulted in a noteworthy decrease in both overshoot and settling time—two crucial elements that guarantee the stability and dependability of the PEMFC system. Fractional-order controllers assist extend fuel cell life and minimize maintenance requirements by preserving a more stable and controlled working environment. This lowers operating costs and boosts overall system efficiency.

5.2 Conclusion

5.2.1 Overall impact of the proposed control strategies

By presenting and validating the usage of fractional-order controllers, the research reported in this thesis has significantly advanced the field of PEMFC control. PEMFC performance has been found to be greatly enhanced by the suggested control methodologies, especially when it comes to pressure control and system stability. The effective execution of these tactics in both simulated and experimental environments underscores their prospective scope for wider deployment in industrial contexts, where upholding elevated efficiency and dependability is vital. The results of the study have important ramifications for PEMFC system operation and design, especially when considering clean technology and renewable energy. Through the improvement of PEMFCs' efficiency and dependability, the suggested control schemes foster the progress of fuel cell technology as a feasible substitute for conventional energy sources.

As a result, this research may spur additional innovation in the clean energy sector, especially in the creation of PEMFC systems that are more dependable and efficient.

This thesis proposes a fractional order PID controller design method for the linearised integer order model. The benefits of fractional order controllers for real dynamical processes are becoming more clear. Two integer order dynamical models are used to illustrate the suggested method for designing fractional order PID controllers, and the simulation results indicate that a fractional order PID controller achieves better control performance when using the suggested design method. The fact that an additional tuning parameter (fractional parameter) provides more freedom in fulfilling design specifications is what spurred this study. The GA based FOPID controller is selected due to its extra parameter adjustment capability, which improves control performance over a conventional PID controller.

In this thesis, a dynamic nonlinear model for the PEM fuel cell is developed, and various control strategies are proposed to regulate the supply manifold pressure of the system. The FOPTD approximation technique is used in the research to design the controllers, and the plant's performance is assessed in terms of set-point surveillance and error reduction. Additionally, examine how system factors impact the plant equivalent circuit using uncertainty analysis. With a settling time of about 0.9 seconds and a steady-state error of less than 5%, the results demonstrate how well the IO model and IO control technique with FPI regulate the supply manifold pressure. The IO model and IO control strategy were defeated by the FMFPI strategy and the first-order plus dead time model-based FO model FO control strategy, respectively. With a steady-state error of less than 0.5% and a settling time of roughly 0.4 seconds, the plant operates noticeably better with this method. The best approach is to use a fractional model with a fractional controller for supply manifold pressure control. Furthermore, our uncertainty analysis suggests that the plant equivalent circuit of the PEM

fuel cell is very sensitive to system characteristics, such as the cell temperature, the pressure drop across the cell, and the oxygen usage factor. These results emphasise how crucial it is to take plant performance into account when designing control systems for PEMFCs. This thesis also presents a novel approach to designing control scheme for PEMFCs, which offers important insights into the plant equivalent circuit and the impact of system parameters on plant performance. Our results demonstrate the effectiveness of advanced control strategies, such as the FO model FO control strategy, in improving plant performance. These findings have significant implications for the design and optimization of control systems for PEMFCs, which are increasingly recognized as a promising technology for clean energy production.

Lastly, this study uses a range of control techniques, such as normal PI, PSO-FOPI, GA-FOPI, and GWO-FOPI controllers, to manage the DC/DC converter and enhance the performance of proton exchange membrane fuel cells (PEMFC). The optimal system parameters were identified using the Simulink models utilised for this investigation using fitness functions including IAE, ISTE, and ITAE. These parameters were then assessed according to performance. Important parameters like settling time, maximum overshoot percentage, and fitness function value were used to test the performance. The research was conducted in two phases. Optimal settings based on fitness functions were established in the first phase using the PSO-FOPI and GA-FOPI controllers. In order to identify the best methodology, the second phase compares approaches according to settling time and maximum overshoot percentage. According to the results, the IAE and ISTE fitness functions outperformed the others when it came to minimising overshoot and settling time. According to the study, the suggested controllers (PSO-PI, PSO-FOPI, GA-PI, and GWO-FOPI) performed better than the standard PI controller, particularly when it came to starting power

usage, where the PI approach used more power. On the other hand, the new techniques led to reduced power consumption, which is in line with previous studies.

5.2.2 Practical Implications for PEMFC Operation and Efficiency

The suggested control mechanisms have broad practical consequences. Fractional-order controllers are especially well-suited for PEMFC systems, which are frequently subject to fluctuating operating conditions and nonlinear dynamics, because they may provide more precise and adaptive control. These controllers' improved performance—especially in terms of pressure management—translates into increased system dependability and efficiency.

Because fractional-order controllers require less maintenance and extend the life of PEMFC systems, they can result in significant cost reductions for industrial applications. Because of the increased efficiency, less hydrogen is needed to generate the same amount of power, which can lower operating costs even more and increase the system's overall sustainability.

5.3 Future research directions

5.3.1 Potential Areas for further investigation

Even though this research has advanced the design and validation of fractional-order PEMFC controllers significantly, there are still a few areas that need more study. The use of fractional-order controllers with other fuel cell types, including solid oxide fuel cells (SOFCs) or alkaline fuel cells (AFCs), is one possible direction for future research. It would be fascinating to investigate whether the advantages of fractional-order control can be extended to these other technologies, as these systems present their own distinct challenges and dynamics.

The integration of fractional-order controllers with other sophisticated control strategies, including adaptive control or model predictive control (MPC), is another possible topic for

future study. Combining these methods with fractional-order control could result in even more reliable and effective control schemes for PEMFCs and other complicated systems. Each of these methods has advantages of its own.

Additionally, more investigation might look into the design and optimization of fractional-order controllers using artificial intelligence and machine learning. It might be able to create even more intricate and adaptive control schemes that are more suited to managing the intricacies of PEMFC systems and other nonlinear, time-varying systems by utilizing AI.

5.3.2 Application of Fractional-Order Control Techniques to Other Energy Systems

The efficacy of fractional-order controllers in photovoltaic systems implies that these methods may also be useful in other energy systems. Fractional-order control, for instance, might be used to regulate renewable energy systems, like photovoltaic (PV) or wind turbines, which are likewise susceptible to nonlinear dynamics and changeable operating circumstances.

Fractional-order control techniques used to these systems may result in increased reliability and efficiency comparable to that seen in PEMFC systems. As a result, this research creates new avenues for the application of fractional-order control in a variety of energy systems, advancing the creation of energy technologies that are more sustainable and efficient.

5.4 Final remarks

5.4.1 Summary of the Thesis and Its Contributions to the Field

In conclusion, by developing and confirming the usage of fractional-order controllers, this thesis has significantly advanced the field of PEMFC control. The results of the research show how well these controllers work to maximize PEMFC system performance, especially when it comes to pressure control and system stability. It has been demonstrated that the

suggested control techniques work better than conventional integer-order controllers, which boosts system reliability, lowers maintenance costs, and improves efficiency.

Additionally, the study has shown how fractional-order controllers can be used in different energy systems, creating new opportunities for clean energy research and innovation. The results of this thesis have important ramifications for both the PEMFC system's design and operation as well as for the larger field of renewable energy technology.

To sum up, this study has established the foundation for the advancement and utilization of fractional-order control methods in various energy systems. The results of this thesis could spur additional innovation in the clean energy sector and aid in the creation of energy solutions that are more dependable, efficient, and sustainable.

Appendix

Appendix 1. Model parameters and constants

Table A1. Constants of the PEMFC system model.

$c_1 = \frac{RT_{st} K_{cathode,in}}{M_{O_2} V_{ca}} \left(\frac{X_{O_2,atm}}{1 + \omega_{atm}} \right)$	$c_2 = P_{sat}$	$c_3 = \frac{RT_{st}}{V_{cathode}}$
$c_4 = M_{O_2}$	$c_5 = M_{N_2}$	$c_6 = M_V P_{sat}$
$X_{O_2,atm} = \frac{y_{O_2,atm} M_{O_2}}{M_{a,atm}}$	$c_7 = \frac{RT_{st} n}{4FV_{ca}}$	$c_8 = \frac{RT_{st} K_{cathode,in}}{M_{N_2} V_{ca}} \left(\frac{1 - X_{O_2,atm}}{1 + \omega_{atm}} \right)$
$c_9 = \frac{\eta_{cm} K_t K_v}{J_{cp} R_{cm}}$	$c_{10} = \frac{C_p T_{atm}}{J_{cp} \eta_{cp}}$	$c_{11} = P_{atm}$
$c_{12} = \frac{\gamma - 1}{\gamma}$	$\omega_{atm} = \frac{M_v \Phi_{atm} P_{sat}}{M_{a,atm} P_{atm} - \Phi_{atm} P_{sat}}$	$c_{13} = \frac{\eta_{cm} K_t}{J_{cp} R_{cm}}$
$c_{14} = \frac{RT_{atm} \gamma}{M_{a,atm} V_{sm}}$	$c_{15} = \frac{1}{\eta_{cp}}$	$c_{16} = K_{cathode_in}$

References

- Daud, W. R. W., Rosli, R. E., Majlan, E. H., Hamid, S. A. A., Mohamed, R., & Husaini, T. (2017). PEM fuel cell system control: A review. *Renewable Energy*, *113*, 620-638.
- Van Der Linden, F., Pahon, E., Morando, S., & Bouquain, D. (2023). A review on the Proton-Exchange Membrane Fuel Cell break-in physical principles, activation procedures, and characterization methods. *Journal of Power Sources*, *575*, 233168.
- Pollet, B. G., Kocha, S. S., & Staffell, I. (2019). Current status of automotive fuel cells for sustainable transport. *Current opinion in Electrochemistry*, *16*, 90-95.
- Hou, Y., Schneider, P., Ney, L., & Zamel, N. (2024). Optimizing catalyst layer composition of PEM fuel cell via machine learning: Insights from in-house experimental data. *Energy and AI*, *18*, 100439
- Cooper, J. S. (2004). Design analysis of PEMFC bipolar plates considering stack manufacturing and environment impact. *Journal of Power Sources*, *129*(2), 152-169.
- Braga, L. B., Silveira, J. L., da Silva, M. E., Machin, E. B., Pedroso, D. T., & Tuna, C. E. (2014). Comparative analysis between a PEM fuel cell and an internal combustion engine driving an electricity generator: Technical, economical and ecological aspects. *Applied Thermal Engineering*, *63*(1), 354-361.
- Gencoglu, M. T., & Ural, Z. (2009). Design of a PEM fuel cell system for residential application. *International journal of hydrogen energy*, *34*(12), 5242-5248.
- Fan, L., Xing, L., Tu, Z., & Chan, S. H. (2021). A breakthrough hydrogen and oxygen utilization in a H₂-O₂ PEMFC stack with dead-ended anode and cathode. *Energy Conversion and Management*, *243*, 114404.
- Van Nguyen, T., & Knobbe, M. W. (2003). A liquid water management strategy for PEM fuel cell stacks. *Journal of Power Sources*, *114*(1), 70-79.

- Li, B., Wan, K., Xie, M., Chu, T., Wang, X., Li, X., & Zhang, C. (2022). Durability degradation mechanism and consistency analysis for proton exchange membrane fuel cell stack. *Applied Energy*, *314*, 119020.
- Cozzolino, R., Cicconardi, S. P., Galloni, E., Minutillo, M., & Perna, A. (2011). Theoretical and experimental investigations on thermal management of a PEMFC stack. *International Journal of Hydrogen Energy*, *36*(13), 8030-8037.
- Choe, S. Y., Ahn, J. W., Lee, J. G., & Baek, S. H. (2008). Dynamic simulator for a PEM fuel cell system with a PWM DC/DC converter. *IEEE Transactions on Energy Conversion*, *23*(2), 669-680.
- Gerbec, M., Jovan, V., & Petrovčič, J. (2008). Operational and safety analyses of a commercial PEMFC system. *International journal of hydrogen energy*, *33*(15), 4147-4160.
- Curtin, D. E., Lousenberg, R. D., Henry, T. J., Tangeman, P. C., & Tisack, M. E. (2004). Advanced materials for improved PEMFC performance and life. *Journal of power Sources*, *131*(1-2), 41-48.
- Williams, M. V., Begg, E., Bonville, L., Kunz, H. R., & Fenton, J. M. (2004). Characterization of gas diffusion layers for PEMFC. *Journal of the Electrochemical Society*, *151*(8), A1173.
- Swain, P., & Jena, D. (2015, March). PID control design for the pressure regulation of PEM fuel cell. In *2015 International Conference on Recent Developments in Control, Automation and Power Engineering (RDCAPE)* (pp. 286-291). IEEE.
- Wilberforce, T., Rezk, H., Olabi, A. G., Epelle, E. I., & Abdelkareem, M. A. (2023). Comparative analysis on parametric estimation of a PEM fuel cell using metaheuristics algorithms. *Energy*, *262*, 125530.

- Rajalakshmi, N., & Dhathathreyan, K. S. (2007). Catalyst layer in PEMFC electrodes—Fabrication, characterisation and analysis. *Chemical Engineering Journal*, 129(1-3), 31-40.
- Han, M., Xu, J. H., Chan, S. H., & Jiang, S. P. (2008). Characterization of gas diffusion layers for PEMFC. *Electrochimica acta*, 53(16), 5361-5367.
- Spiegel, C. (2011). PEM fuel cell modeling and simulation using MATLAB. Elsevier.
- Wang, H., & Turner, J. A. (2010). Reviewing metallic PEMFC bipolar plates. *Fuel cells*, 10(4), 510-519.
- Hwang, J. J. (2013). Thermal control and performance assessment of a proton exchanger membrane fuel cell generator. *Applied energy*, 108, 184-193.
- Bao, C., Ouyang, M., & Yi, B. (2006). Modeling and control of air stream and hydrogen flow with recirculation in a PEM fuel cell system—I. Control-oriented modeling. *International journal of hydrogen energy*, 31(13), 1879-1896.
- Berg, P., Promislow, K., Pierre, J. S., Stumper, J., & Wetton, B. (2004). Water management in PEM fuel cells. *Journal of the Electrochemical Society*, 151(3), A341.
- Fan, L., Xing, L., Tu, Z., & Chan, S. H. (2021). A breakthrough hydrogen and oxygen utilization in a H₂-O₂ PEMFC stack with dead-ended anode and cathode. *Energy Conversion and Management*, 243, 114404.
- Gerard, M., Poirot-Crouvezier, J. P., Hissel, D., & Pera, M. C. (2010). Oxygen starvation analysis during air feeding faults in PEMFC. *International Journal of Hydrogen Energy*, 35(22), 12295-12307.

- Liu, P., Xu, S., Fu, J., & Liu, C. (2020). Experimental investigation on the voltage uniformity for a PEMFC stack with different dynamic loading strategies. *International Journal of Hydrogen Energy*, 45(50), 26490-26500.
- Ijaodola, O. S., El-Hassan, Z., Ogungbemi, E., Khatib, F. N., Wilberforce, T., Thompson, J., & Olabi, A. G. (2019). Energy efficiency improvements by investigating the water flooding management on proton exchange membrane fuel cell (PEMFC). *Energy*, 179, 246-267.
- Li, Y., Pei, P., Wu, Z., Ren, P., Jia, X., Chen, D., & Huang, S. (2018). Approaches to avoid flooding in association with pressure drop in proton exchange membrane fuel cells. *Applied energy*, 224, 42-51.
- Dafalla, A. M., & Jiang, F. (2018). Stresses and their impacts on proton exchange membrane fuel cells: A review. *International Journal of Hydrogen Energy*, 43(4), 2327-2348.
- Omrani, R., Seif Mohammadi, S., Mafinejad, Y., Paul, B., Islam, R., & Shabani, B. (2019). PEMFC purging at low operating temperatures: An experimental approach. *International Journal of Energy Research*, 43(13), 7496-7507.
- Xue, D. (2017). Fractional-order control systems: fundamentals and numerical implementations (Vol. 1). Walter de Gruyter GmbH & Co KG.
- Chen, Y., Petras, I., & Xue, D. (2009, June). Fractional order control-a tutorial. In *2009 American control conference* (pp. 1397-1411). IEEE.
- Krishnakumar, K., & Goldberg, D. E. (1992). Control system optimization using genetic algorithms. *Journal of Guidance, Control, and Dynamics*, 15(3), 735-740.
- Jaiswal, S., Suresh Kumar, C., Seepana, M. M., & Babu, G. U. B. (2020). Design of fractional order PID controller using genetic algorithm optimization technique for nonlinear system. *Chemical Product and Process Modeling*, 15(2), 20190072.

- Anil, G., Siva, M., Srinath, S., & Uday Bhaskar Babu, G. (2021). Designing of Fractional-Order PI/PID Controller by Meta-heuristic Algorithm Using PSO for PEM Fuel Cell. *Intelligent Algorithms for Analysis and Control of Dynamical Systems*, 125-131.
- Silaa, M. Y., Barambones, O., Derbeli, M., Napole, C., & Bencherif, A. (2022). Fractional order PID design for a proton exchange membrane fuel cell system using an extended grey wolf optimizer. *Processes*, *10*(3), 450.
- Wang, Y., Li, H., Feng, H., Han, K., He, S., & Gao, M. (2021). Simulation study on the PEMFC oxygen starvation based on the coupling algorithm of model predictive control and PID. *Energy Conversion and Management*, *249*, 114851.
- Filo, M., Kumar, S., & Khammash, M. (2022). A hierarchy of biomolecular proportional-integral-derivative feedback controllers for robust perfect adaptation and dynamic performance. *Nature communications*, *13*(1), 2119.
- Mohanty, S., & Sengupta, A. (2021, January). Decentralized Control of Multi-Input Multi-Output Processes Using Effective Transfer Function Method. In *2021 IEEE Second International Conference on Control, Measurement and Instrumentation (CMI)* (pp. 160-165). IEEE.
- Utkin, V. I., & Poznyak, A. S. (2013). Adaptive sliding mode control. *Advances in Sliding Mode Control: Concept, Theory and Implementation*, 21-53.
- Lin, F., Brandt, R. D., & Saikalas, G. (2000). Self-tuning of PID controllers by adaptive interaction. In *Proceedings of the 2000 American Control Conference. ACC (IEEE Cat. No. 00CH36334)* (Vol. 5, pp. 3676-3681). IEEE.
- Lavretsky, E., & Wise, K. A. (2012). Robust adaptive control. In *Robust and adaptive control: With aerospace applications* (pp. 317-353). London: Springer London.

-
- Koerber, A., & King, R. (2013). Combined feedback–feedforward control of wind turbines using state-constrained model predictive control. *IEEE Transactions on Control Systems Technology*, 21(4), 1117-1128.
- Van Hessem, D., & Bosgra, O. (2006). Stochastic closed-loop model predictive control of continuous nonlinear chemical processes. *Journal of Process Control*, 16(3), 225-241.
- Jemeï Jemeï, S., Hissel, D., Péra Pera, M. C., & Kauffmann, J. M. (2008). A new modeling approach of embedded fuel-cell power generators based on artificial neural network. *IEEE Transactions on Industrial Electronics*, 55(1), 437-447.
- Gulcehre, C., Chandar, S., Cho, K., & Bengio, Y. (2018). Dynamic neural Turing machine with continuous and discrete addressing schemes. *Neural computation*, 30(4), 857-884.
- Benchouia, N. E., Derghal, A., Mahmah, B., Madi, B., Khochemane, L., & Aoul, E. H. (2015). An adaptive fuzzy logic controller (AFLC) for PEMFC fuel cell. *International Journal of Hydrogen Energy*, 40(39), 13806-13819.
- Ashraf, H., Abdellatif, S. O., Elkholy, M. M., & El-Fergany, A. A. (2022). Computational techniques based on artificial intelligence for extracting optimal parameters of PEMFCs: Survey and insights. *Archives of Computational Methods in Engineering*, 29(6), 3943-3972.
- Lü, X., Qu, Y., Wang, Y., Qin, C., & Liu, G. (2018). A comprehensive review on hybrid power system for PEMFC-HEV: Issues and strategies. *Energy conversion and Management*, 171, 1273-1291.
- Sharma, S., Mullapudi, S., Araga, R., Patle, D. S., & Gara, U. B. B. (2023). Design of model-based control strategies for a novel MISO PEM fuel cell control structure. *Environmental Science and Pollution Research*, 30(22), 61586-61605.
-

- Ferng, Y. M., & Su, A. (2007). A three-dimensional full-cell CFD model used to investigate the effects of different flow channel designs on PEMFC performance. *International Journal of Hydrogen Energy*, 32(17), 4466-4476.
- Lin, G., & Van Nguyen, T. (2006). A two-dimensional two-phase model of a PEM fuel cell. *Journal of the Electrochemical Society*, 153(2), A372.
- Chen, J., Liu, Z., Wang, F., Ouyang, Q., & Su, H. (2017). Optimal oxygen excess ratio control for PEM fuel cells. *IEEE Transactions on Control Systems Technology*, 26(5), 1711-1721.
- Damour, C., Benne, M., Grondin-Perez, B., Chabriat, J. P., & Pollet, B. G. (2015). A novel non-linear model-based control strategy to improve PEMFC water management—The flatness-based approach. *International Journal of Hydrogen Energy*, 40(5), 2371-2376.
- Omer Abbaker, A. M., Wang, H., & Tian, Y. (2020). Robust model-free adaptive interval type-2 fuzzy sliding mode control for PEMFC system using disturbance observer. *International Journal of Fuzzy Systems*, 22, 2188-2203.
- Benchouia, N. E., Derghal, A., Mahmah, B., Madi, B., Khochemane, L., & Aoul, E. H. (2015). An adaptive fuzzy logic controller (AFLC) for PEMFC fuel cell. *International Journal of Hydrogen Energy*, 40(39), 13806-13819.
- Silaa, M. Y., Derbeli, M., Barambones, O., & Cheknane, A. (2020). Design and implementation of high order sliding mode control for PEMFC power system. *Energies*, 13(17), 4317.
- Divi, S., Sonawane, S. H., & Das, S. (2019). Uncertainty analysis of transfer function of proton exchange membrane fuel cell and design of PI/PID controller for supply manifold pressure control. *Indian Chemical Engineer*, 61(2), 138-152.

-
- Chinesta, F., Huerta, A., Rozza, G., & Willcox, K. (2016). Model order reduction. *Encyclopedia of computational mechanics*, 1-36.
- Grimholt, C., & Skogestad, S. (2012). Optimal PI-control and verification of the SIMC tuning rule. *IFAC Proceedings Volumes*, 45(3), 11-22.
- Chen, X., Fang, Y., Liu, Q., He, L., Zhao, Y., Huang, T., & Wang, X. (2022). Temperature and voltage dynamic control of PEMFC Stack using MPC method. *Energy Reports*, 8, 798-808.
- Kirubakaran, A., Jain, S., & Nema, R. K. (2009). A review on fuel cell technologies and power electronic interface. *Renewable and sustainable energy reviews*, 13(9), 2430-2440.
- El-Khazali, R. (2013). Fractional-order PI λ D μ controller design. *Computers & Mathematics with Applications*, 66(5), 639-646.
- Zhang, L., Pan, M., & Quan, S. (2008). Model predictive control of water management in PEMFC. *Journal of Power Sources*, 180(1), 322-329.
- Grimholt, C., & Skogestad, S. (2012). Optimal PI-control and verification of the SIMC tuning rule. *IFAC Proceedings Volumes*, 45(3), 11-22.
- Lee, H. K., Park, J. H., Kim, D. Y., & Lee, T. H. (2004). A study on the characteristics of the diffusion layer thickness and porosity of the PEMFC. *Journal of Power Sources*, 131(1-2), 200-206.
- Rosli, N. A. H., Loh, K. S., Wong, W. Y., Yunus, R. M., Lee, T. K., Ahmad, A., & Chong, S. T. (2020). Review of chitosan-based polymers as proton exchange membranes and roles of chitosan-supported ionic liquids. *International journal of molecular sciences*, 21(2), 632.

-
- Sierociuk, D., & Macias, M. (2013, May). Comparison of variable fractional order PID controller for different types of variable order derivatives. In *Proceedings of the 14th International Carpathian Control Conference (ICCC)* (pp. 334-339). IEEE.
- Yarat, S., Senan, S., & Orman, Z. (2021). A comparative study on PSO with other metaheuristic methods. *Applying particle swarm optimization: New solutions and cases for optimized portfolios*, 49-72.
- Podlubny, I. (1994). Fractional-order systems and fractional-order controllers. *Institute of Experimental Physics, Slovak Academy of Sciences, Kosice*, 12(3), 1-18.
- Monje, C. A., Vinagre, B. M., Feliu, V., & Chen, Y. (2008). Tuning and auto-tuning of fractional order controllers for industry applications. *Control engineering practice*, 16(7), 798-812.
- Ababneh, M., Salah, M., & Alwidyan, K. (2011). Linearization of nonlinear dynamical systems: A comparative study. *Jordan Journal of Mechanical and Industrial Engineering*.
- Park, G. H. (2014). *Modeling and control of proton exchange membrane and solid oxide fuel cells and solar cells*. Rutgers The State University of New Jersey, School of Graduate Studies.
- Routh, A., Ghosh, S., Dey, I., Rahaman, M., & Ghosh, A. (2024). Optimization of PEMFC pressure control using fractional PI/D controller with non-integer order: design and experimental evaluation. *Engineering Research Express*, 6(2), 025001.
- Routh, A., Ghosh, S., Rahaman, M., & Ghosh, A. (2023). Fractional $PI^\lambda D^\mu$ controller design for non-linear PEM fuel cell for pressure control based on a genetic algorithm. *Indian Chemical Engineer*, 65(2), 125-142.
-

- Cai, S., Li, X., Yang, L., Hua, Z., Li, S., & Tu, Z. (2024). Demand flexibility and its impact on a PEM fuel cell-based integrated energy supply system with humidity control. *Renewable Energy*, 228, 120600.
- Ogbonnaya, C., Turan, A., & Abeykoon, C. (2020). Modularization of integrated photovoltaic-fuel cell system for remote distributed power systems. In *Industry 4.0—Shaping The Future of The Digital World* (pp. 303-308). CRC Press
- Vasilyev, A., Andrews, J., Dunnett, S. J., & Jackson, L. M. (2021). Dynamic reliability assessment of PEM fuel cell systems. *Reliability Engineering & System Safety*, 210, 107539.
- Wang, S., & Jiang, S. P. (2017). Prospects of fuel cell technologies. *National Science Review*, 4(2), 163-166.
- Ziane, M. A., Join, C., Benne, M., Damour, C., Steiner, N. Y., & Péra, M. C. (2023). A new concept of water management diagnosis for a PEM fuel cell system. *Energy Conversion and Management*, 285, 116986.
- Prokop, M., Drakselova, M., & Bouzek, K. (2020). Review of the experimental study and prediction of Pt-based catalyst degradation during PEM fuel cell operation. *Current Opinion in Electrochemistry*, 20, 20-27.
- Wu, D., Peng, C., Yin, C., & Tang, H. (2020). Review of system integration and control of proton exchange membrane fuel cells. *Electrochemical Energy Reviews*, 3, 466-505.
- Hai, T., Aksoy, M., & Rezvani, A. (2024). Optimal energy management and scheduling of a microgrid considering hydrogen storage and PEMFC with uncertainties. *International Journal of Hydrogen Energy*, 88, 1017-1033.

Xu, J., Zhang, C., Wan, Z., Chen, X., Chan, S. H., & Tu, Z. (2022). Progress and perspectives of integrated thermal management systems in PEM fuel cell vehicles: A review. *Renewable and Sustainable Energy Reviews*, *155*, 111908.

Pandiyan, S., Elayaperumal, A., Rajalakshmi, N., Dhathathreyan, K. S., & Venkateshwaran, N. (2013). Design and analysis of a proton exchange membrane fuel cells (PEMFC). *Renewable energy*, *49*, 161-165.

Colombo, E., Baricci, A., Mora, D., Guetaz, L., & Casalegno, A. (2023). An innovative accelerated stress test representative of automotive PEMFC degradation mechanisms validated on 1000 hours real-world operation. *Journal of Power Sources*, *580*, 233376.

Lee, F. C., Ismail, M. S., Ingham, D. B., Hughes, K. J., Ma, L., Lyth, S. M., & Pourkashanian, M. (2022). Alternative architectures and materials for PEMFC gas diffusion layers: A review and outlook. *Renewable and Sustainable Energy Reviews*, *166*, 112640.

Lu, J. B., Wei, G. H., Zhu, F. J., Yan, X. H., & Zhang, J. L. (2019). Pressure effect on the PEMFC performance. *Fuel Cells*, *19*(3), 211-220.

Chen, H., Xu, S., Pei, P., Qu, B., & Zhang, T. (2019). Mechanism analysis of starvation in PEMFC based on external characteristics. *International Journal of Hydrogen Energy*, *44*(11), 5437-5446.

Wang, X., Ni, Z., Yang, Z., Wang, Y., & Han, K. (2024). Optimization of PEMFC operating parameters considering water management by an integrated method of sensitivity analysis, multi-objective optimization and evaluation. *Energy Conversion and Management*, *321*, 119057.

- Søndergaard, S., Cleemann, L. N., Jensen, J. O., & Bjerrum, N. J. (2019). Influence of oxygen on the cathode in HT-PEM fuel cells. *International Journal of Hydrogen Energy*, *44*(36), 20379-20388.
- Gul, F., Rahiman, W., Alhady, S. N., Ali, A., Mir, I., & Jalil, A. (2021). Meta-heuristic approach for solving multi-objective path planning for autonomous guided robot using PSO–GWO optimization algorithm with evolutionary programming. *Journal of Ambient Intelligence and Humanized Computing*, *12*(7), 7873-7890.
- Taleb, M. A., Béthoux, O., & Godoy, E. (2017). Identification of a PEMFC fractional order model. *International Journal of Hydrogen Energy*, *42*(2), 1499-1509.
- Qi, Z., Sun, Q., Ge, W., & He, Y. (2020). Nonlinear modeling of PEMFC based on fractional order subspace identification. *Asian Journal of Control*, *22*(5), 1892-1900.
- Baroutaji, A., Arjunan, A., Robinson, J., Wilberforce, T., Abdelkareem, M. A., & Olabi, A. G. (2021). PEMFC poly-generation systems: developments, merits, and challenges. *Sustainability*, *13*(21), 11696.
- Borup, R. L., Kusoglu, A., Neyerlin, K. C., Mukundan, R., Ahluwalia, R. K., Cullen, D. A., ... & Myers, D. J. (2020). Recent developments in catalyst-related PEM fuel cell durability. *Current Opinion in Electrochemistry*, *21*, 192-200.
- Rosli, R. E., Sulong, A. B., Daud, W. R. W., Zulkifley, M. A., Husaini, T., Rosli, M. I., ... & Haque, M. A. (2017). A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system. *International Journal of Hydrogen Energy*, *42*(14), 9293-9314.
- He, Y., Tan, Q., Lu, L., Sokolowski, J., & Wu, G. (2019). Metal-nitrogen-carbon catalysts for oxygen reduction in PEM fuel cells: self-template synthesis approach to enhancing catalytic activity and stability. *Electrochemical Energy Reviews*, *2*, 231-251.

- Knospe, C. (2006). PID control. *IEEE Control Systems Magazine*, 26(1), 30-31.
- Ziogou, C., Voutetakis, S., Georgiadis, M. C., & Papadopoulou, S. (2018). Model predictive control (MPC) strategies for PEM fuel cell systems—A comparative experimental demonstration. *Chemical Engineering Research and Design*, 131, 656-670.
- Zhang, J., Liu, G., Yu, W., & Ouyang, M. (2008). Adaptive control of the airflow of a PEM fuel cell system. *Journal of Power Sources*, 179(2), 649-659.
- Dyanty, N., Parsons, A., Bujlo, P., & Pasupathi, S. (2019). Behavioural study of PEMFC during start-up/shutdown cycling for aeronautic applications. *Materials for Renewable and Sustainable Energy*, 8, 1-8.
- Guo, Y., Pan, F., Chen, W., Ding, Z., Yang, D., Li, B., & Zhang, C. (2021). The controllable design of catalyst inks to enhance PEMFC performance: A review. *Electrochemical Energy Reviews*, 4, 67-100.
- Maiyalagan, T., & Pasupathi, S. (2010). Components for PEM fuel cells: An overview. In *Materials science forum* (Vol. 657, pp. 143-189). Trans Tech Publications Ltd.
- Prass, S., St-Pierre, J., Klingele, M., Friedrich, K. A., & Zamel, N. (2021). Hydrogen oxidation artifact during platinum oxide reduction in cyclic voltammetry analysis of low-loaded PEMFC electrodes. *Electrocatalysis*, 12, 45-55.
- Sassin, M. B., Garsany, Y., Atkinson Iii, R. W., Hjelm, R. M. E., & Swider-Lyons, K. E. (2019). Understanding the interplay between cathode catalyst layer porosity and thickness on transport limitations en route to high-performance PEMFCs. *International Journal of Hydrogen Energy*, 44(31), 16944-16955.
- Han, M., Xu, J. H., Chan, S. H., & Jiang, S. P. (2008). Characterization of gas diffusion layers for PEMFC. *Electrochimica acta*, 53(16), 5361-5367.

Božić, M., Vasiljević-Toskić, M., Bodić, M., & Rajs, V. (2020). Advantages of a combination of PD and PID controller over PID controller in the example of quadcopter control and stabilization.

Copeland, B. R. (2008). The design of PID controllers using Ziegler Nichols tuning. *Ziegler-Nicholos Method*.

Sung, S. W., & Lee, I. B. (1996). Limitations and countermeasures of PID controllers. *Industrial & engineering chemistry research*, 35(8), 2596-2610.

Bingi, K., Ibrahim, R., Karsiti, M. N., Hassan, S. M., & Harindran, V. R. (2020). *Fractional-order systems and PID controllers* (Vol. 264). Cham, Switzerland: Springer International Publishing.

Soukkou, A., Belhour, M. C., & Leulmi, S. (2016). Review, design, optimization and stability analysis of fractional-order PID controller. *International Journal of Intelligent Systems and Applications*, 8(7), 73.

Faris, H., Aljarah, I., Al-Betar, M. A., & Mirjalili, S. (2018). Grey wolf optimizer: a review of recent variants and applications. *Neural computing and applications*, 30, 413-435.

Sharma, P., Cirrincione, M., Mohammadi, A., Cirrincione, G., & Kumar, R. R. (2024). An overview of artificial intelligence-based techniques for PEMFC system diagnosis. *IEEE Access*.

Nernst, W. (1889). Die elektromotorische wirksamkeit der jonen. *Zeitschrift für physikalische Chemie*, 4(1), 129-181.

Suh, K. W. (2006). Modelling, analysis and control of fuel cell hybrid power systems. University of Michigan.

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