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Intitulé

*Two Types of Fuzzy Logic Controllers for the
Fuel and Oxygen Flows of the Solid Oxide Fuel
Cell*

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Dedication

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Abstract

Solid Oxide Fuel Cells (SOFCs) are highly efficient and environmentally friendly energy systems; however, their nonlinear dynamics and sensitivity to input variations present significant control challenges. One of the most critical aspects of SOFC operation is output voltage regulation, which directly impacts system stability, efficiency, and seamless integration with external loads or power grids.

To ensure a stable output voltage under varying operating conditions-such as load fluctuations or changes in fuel composition-advanced control strategies are necessary. Effective regulation requires precise management of key variables, particularly fuel and oxygen flow rates, which directly influence electrochemical reactions and, consequently, the SOFC's output voltage.

This study conducts a comparative analysis of three distinct control strategies for SOFC voltage regulation:

- PID Controller A widely used method favored for its simplicity, but often insufficient when dealing with nonlinearities and uncertainties.
- Type-1 Fuzzy Logic Controller A rule-based control approach capable of handling moderate system nonlinearities effectively.
- Type-2 Fuzzy Logic Controller An advanced version of T1-FLC that integrates uncertainty into fuzzy sets, providing enhanced robustness in dynamic environments.

Keywords: Solid Oxide Fuel Cell, voltage Regulation, Nonlinear Dynamics, PID Controller, Fuzzy Logic Controller, Fuel and Oxygen Flow Rates, Control Strategies.

Résumé

Les piles à combustible à oxyde solide sont des systèmes énergétiques hautement efficaces et respectueux de l'environnement. Toutefois, leurs dynamiques non linéaires et leur sensibilité aux variations des entrées posent des défis majeurs en matière de contrôle. L'un des aspects les plus cruciaux du fonctionnement des SOFC est la régulation de la tension de sortie, qui influe directement sur la stabilité du système, son efficacité et son intégration avec des charges externes ou des réseaux électriques.

Pour garantir une tension de sortie stable malgré des conditions d'exploitation variables- telles que des fluctuations de charge ou des modifications de la composition du carburant- des stratégies de contrôle avancées sont nécessaires. Une gestion efficace implique une régulation précise des principaux paramètres, notamment les débits de carburant et d'oxygène, qui influencent directement les réactions électrochimiques et, par conséquent, la tension de sortie des SOFC.

Cette étude réalise une analyse comparative de trois stratégies de contrôle distinctes pour la régulation de la tension des SOFC :

- Contrôleur PID - Méthode largement utilisée pour sa simplicité, mais insuffisante face aux non-linéarités et incertitudes du système.
- Contrôleur flou de type-1, une approche basée sur des règles, efficace pour gérer une non-linéarité modérée.
- Contrôleur flou de type-2 Une amélioration du T1 FLC intégrant l'incertitude dans les ensembles flous, offrant une robustesse accrue dans des environnements dynamiques.

Mots-clés : Pile à combustible à oxyde solide (SOFC), Régulation de la tension, Dynamiques non linéaires, Contrôleur PID, Contrôleur flou, Débits de carburant et d'oxygène, Stratégies de contrôle.

ملخص

خلايا وقود الأكسيد الصلب (SOFCs) هي أنظمة طاقة عالية الكفاءة وصديقة للبيئة؛ إلا أن ديناميكياتها غير الخطية وحساسيتها لتغيرات المدخلات تشكل تحديات كبيرة في التحكم. يُعد تنظيم جهد الخرج من أهم جوانب تشغيل خلايا وقود الأكسيد الصلب، والذي يؤثر بشكل مباشر على استقرار النظام وكفاءته وتكامله السلس مع الأحمال الخارجية أو شبكات الطاقة.

لضمان استقرار جهد الخرج في ظل ظروف تشغيل متفاوتة - مثل تقلبات الأحمال أو تغيرات تركيب الوقود - تُعد استراتيجيات التحكم المتقدمة ضرورية. يتطلب التنظيم الفعال إدارة دقيقة للمتغيرات الرئيسية، وخاصة معدلات تدفق الوقود والأكسجين، والتي تؤثر بشكل مباشر على التفاعلات الكهروكيميائية، وبالتالي على جهد خرج خلايا وقود الأكسيد الصلب.

تُجري هذه الدراسة تحليلاً مقارناً لثلاث استراتيجيات تحكم مميزة لتنظيم جهد خلايا وقود الأكسيد الصلب:

- وحدة تحكم PID: وهي طريقة شائعة الاستخدام ومفضلة لبساطتها، ولكنها غالباً ما تكون غير كافية عند التعامل مع حالات عدم الخطية وعدم اليقين.

- وحدة تحكم منطقي ضبابي من النوع 1: وهي نهج تحكم قائم على القواعد قادر على التعامل بفعالية مع حالات عدم الخطية المعتدلة في النظام.

• وحدة تحكم المنطق الضبابي من النوع 2 وهي نسخة متقدمة من T1-FLC تدمج عدم اليقين في المجموعات الضبابية، مما يوفر قوة تحمل محسنة في البيانات الديناميكية.

الكلمات المفتاحية: خلايا وقود الأكسيد الصلب (SOFC)، تنظيم التوتر، الديناميكيات غير الخطية، جهاز التحكم PID، جهاز التحكم في التدفق، تدفق الكربون والأكسجين، استراتيجيات التحكم.

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List of Abbreviations

SOFC	Solid Oxid Fuel Cell
MCFCs	Moltem Carbonate Fuel Cells
PAFCs	Polymer Acid Fuel Cells Molten Carbonate Fuel Cells
FLC	Fuzzy Logic Controller
PID	Proportional-Integral-Derivative
PEM	Polymer Electrolyte Membrane
SOEC	Solid Oxide Electrolyzer Cell
FCEV	Fuel Cell Electric Vehicle
ITAE	Integral of Time-weighted Absolute Error
T1-FLC	Type-1 Fuzzy Logic Controller
T2-FLC	Type-2 Fuzzy Logic Controller
T2-FIS	Type-2 Fuzzy Inference System
YSZ	Yttria-Stabilized Zirconia
EMF	Electromotive Force
MEA	Membrane Electrode Assembly

List of Symbols

Λ_s	Thermal conductivity	2 W/(m·K)
F	Faraday's constant	96,486 C/mol
T	Relaxation time	200 s
R	Universal gas constant	8.31 J/(mol·K)
P	Density	6600 kg/m ³
V°	Ideal standard potential	1.1 V
C_p	Heat capacity	400 J/(kg·K)
N	Number of cells in stack	384
T_0	Initial temperature	1273 K
U_f	Fuel utilization factor	—
V_{fc}	Output voltage of fuel cell	V
V_{act}	Activation loss	V
V_{ohm}	Ohmic loss	V
V_{conc}	Concentration loss	V
$ Fo$	Fourier number	—
S_0	Source term number	—
A	Pre-exponential factor	101.2 kA/cm ²
H	Efficiency	0.8
T	Response time for hydrogen	26.1 s
R_{cell}	Cell internal resistance	0.2 Ω
E_{act}	Activation energy	120 kJ/mol

General Introduction

The growing need for clean and sustainable energy has driven extensive research into alternative energy sources and efficient conversion technologies. Hydrogen, recognized for its abundance and eco-friendly by-products in fuel cell applications, has gained significant attention as a viable energy carrier. Among various fuel cell technologies, the Solid Oxide Fuel Cell stands out due to its high efficiency, adaptability to different fuels, and potential for seamless integration into renewable energy systems, making it a promising solution for future energy need [1].

Managing Solid Oxide Fuel Cell systems comes with significant challenges. Their nonlinear behavior, sluggish thermal response, and susceptibility to disturbances demand sophisticated control strategies to ensure stability and optimize performance. While classical controllers like PID offer simplicity and effectiveness in ideal conditions, they often struggle to handle uncertainties and dynamic variations in real-world scenarios, necessitating more advanced approaches for robust control [2].

To overcome these challenges, intelligent control techniques like fuzzy logic controllers have garnered significant interest. Fuzzy logic replicates human reasoning, enabling decision-making in uncertain or imprecise conditions. Researchers typically focus on two primary types of fuzzy logic controllers: Type-1, which relies on crisp membership functions, and Type-2, which enhances Type-1 by integrating uncertainty directly within the membership functions, allowing for greater adaptability in dynamic environments [3].

This thesis investigates and compares the performance of Fuzzy Logic Type-1 and Type-2 controllers in regulating the fuel and oxygen flows of SOFC, with the objective of stabilizing its output voltage. The study includes modeling the SOFC system, designing the fuzzy controllers, implementing them in MATLAB/Simulink, and compare the results.

The outcomes of this research aim to provide insight into the effectiveness and suitability of advanced fuzzy control strategies in improving SOFC performance and ensuring robustness in the presence of system uncertainties.

Through comparative analysis, this study offers valuable insights into the effectiveness and suitability of different control strategies in handling the highly dynamic and uncertain behavior of SOFC systems. The findings are expected to advance the development of more robust, adaptive, and intelligent control solutions, paving the way for next-generation clean energy technologies.

Chapter I:

Hydrogen, Electrolyse, Fuel cell and SOFC

I.1 Introduction

Hydrogen has been explored as a substitute energy carrier, and generating electricity from it using a fuel cell produces no local pollution, as the only by-product is pure water [4].

Electrolysis is a process that uses electricity to split water into hydrogen and oxygen, and it takes place in a device known as an electrolyser [5].

A fuel cell converts the chemical energy of hydrogen - or other fuels - into electricity in a clean and efficient way. When hydrogen is used as the fuel, the only by-products are electricity, water, and heat. Fuel cells are highly versatile in their applications: they can operate on various fuels and feedstocks, and they are capable of powering systems ranging from large utility-scale power plants to small devices like laptop computers [6].

I.2 Hydrogen

I.2.1 Definition of hydrogen

Hydrogen is the oldest, lightest and most abundant element in the universe. As a gas it is an ultra-light energy carrier, and when it is burned the only emission it produces is water vapour [7].

It serves as a clean alternative to methane, commonly known as natural gas. It is the most abundant chemical element, accounting for approximately 75% of the universe's mass [8].

Hydrogen (H) is a colorless, odorless, and highly flammable gas that chemically combines with oxygen to form water. It is the lightest known element, with an atomic number of 1, an atomic mass of 1.00797, and a density of 0.0899 grams per liter at 0°C [9].

I.2.2 Key properties of hydrogen

- It has an atomic mass of 1.008 amu and an ionization enthalpy of 1312 kJ/mol [8].
- Hydrogen is not toxic, but it can act as a simple asphyxiant by displacing oxygen in the air [8].
- Under standard conditions, hydrogen exists as a diatomic gas with the chemical formula H_2 [10].
- It is commonly referred to as dihydrogen, hydrogen gas, molecular hydrogen, or simply hydrogen [4].

I.2.3 Types of hydrogen

Hydrogen is categorized into different types based on its production method and environmental impact:

I.2.3.1 Grey, black, and brown hydrogen

Grey hydrogen is produced from fossil fuels like natural gas and coal, making up approximately 95% of global hydrogen production. The primary methods for generating grey hydrogen are steam methane reforming and coal gasification, both of which release carbon dioxide (CO_2) into the atmosphere. Since these emissions are not captured, grey hydrogen is not classified as a low-carbon fuel [11].

Currently, The cost of electricity plays a crucial role in the economical production of green hydrogen [12].

green hydrogen accounts for less than 1% of global hydrogen production, primarily due to its high cost. As of 2021, it was three to five times more expensive than grey hydrogen and twice the cost of blue hydrogen. However, Bloomberg predicts that if current trends continue, the cost of green hydrogen could fall to between 0.70 and 1.60 per kilogram by 2050. This price reduction would make it more appealing to energy utilities and competitive with grey hydrogen, driving increased production [13].

I.2.3.4 Other types of hydrogen

Yellow hydrogen is produced through electrolysis, similar to green hydrogen, but it specifically uses solar power as the electricity source [14].

Turquoise hydrogen is produced through a process called methane pyrolysis, which breaks down methane into hydrogen and solid carbon [15].

Pink hydrogen is generated using electricity from nuclear power, making it a low-carbon energy source for hydrogen production [16].

Hydrogen from biomass is currently one of the most widely used industrial methods for producing hydrogen on a large scale, typically from carbon-based sources like natural gas and biomass [17].

I.2.4 Uses of hydrogen

- Light-duty highway vehicles; can achieve a reduction in emissions of more than 50%—and potentially over 90%—compared to today's gasoline-powered vehicles [18].

- Fuel Production; hydrogen is used in refining crude oil into cleaner fuels like gasoline and diesel. It also helps remove contaminants, such as sulfur, during the refining process [19].
- Agricultural and Chemical Industry; hydrogen is a key raw material in the production of ammonia (NH_3), also known as azane. Ammonia plays a vital role in manufacturing fertilizers used globally in agriculture. Additionally, it serves as an affordable and environmentally friendly refrigerant (R-717) [20].

I.2.5 Hydrogen benefits and considerations

Hydrogen is a versatile energy carrier that can be produced from various domestic resources, offering the potential for near-zero greenhouse gas emissions. Once generated, hydrogen can be used in fuel cells to produce electricity, emitting only water vapor and warm air. It holds significant promise for both the stationary power and transportation sectors.

Can offers a sustainable solution for storing and delivering renewable energy, helping to overcome one of the main challenges of renewables - their intermittency [21].

It is a versatile energy carrier-rather than a primary energy source-that can be produced from various feedstocks and utilized across a wide range of applications. When renewable electricity is used to produce hydrogen via electrolysis, it enables the integration of renewable energy into sectors that are difficult to electrify, such as heavy industry and long-distance transport. Additionally, this process contributes to grid flexibility and resilience, complementing other smart electrification solutions like battery storage, demand response, and vehicle-to-grid systems [22].

In power generation, hydrogen is a key option for storing renewable energy. Both hydrogen and ammonia can be utilized in gas turbines to enhance power system flexibility. Additionally, ammonia could be used in coal-fired power plants to help reduce emissions [23].

Hydrogen plays a central role in achieving global net-zero emissions by 2050 and limiting global warming to 1.5°C [24].

I.2.6 Synergies with renewable energy

Hybrid systems integrating solar, wind, battery energy storage, and hydrogen production creates powerful synergies that significantly enhance the performance, reliability, and flexibility of hybrid renewable energy projects [25].

Similarly, the integration of multiple technologies, combined with control co-design (CCD) in hybrid systems, can also significantly improve the performance of traditional power problematic for mobile applications where space is limited [26].

I.3 Electrolyse

Electrolysis is a process that uses electricity to split water into hydrogen and oxygen, offering a promising pathway for carbon-free hydrogen production. This reaction occurs within a device known as an electrolyzer and can be powered by renewable or nuclear energy sources [27].

Hydrogen produced by electrolyzers has a wide range of applications across multiple sectors. In the energy sector, it serves as a clean and efficient fuel for fuel cells, enabling sustainable electricity generation [28].

I.3.1 Types of electrolyzers

I.3.1.1 Polymer Electrolyte Membrane (PEM) Electrolyzers

PEM electrolysis involves the use of a PEM made from a special polymer. This PEM separates the anode and cathode electrically. At the start of the process, liquid, ultrapure water is supplied to the anode side of the electrolyser. When a voltage is then applied to the two electrodes, protons are released and migrate through the membrane. During this electrochemical process, water is converted into hydrogen and oxygen, with hydrogen forming at the cathode and oxygen at the anode. The advantages of this] method include high power density, excellent flexibility, and minimal space requirements [29]. The equation (I.1) and (I.2) represent the chemical reaction [27]:

Chemical Reactions:



I.3.1.2 Alkaline Electrolyzers

Alkaline water electrolysis is a simple and effective method for hydrogen production.

However, for it to be widely adopted, several challenges must be addressed, including reducing energy consumption, cost, and maintenance, while enhancing reliability, durability, and safety [30].

I.3.1.3 Solid Oxide Electrolyzers (SOECs)

High-temperature Solid Oxide Electrolyser Cells (SOECs); offer a highly efficient and potentially cost-effective method for hydrogen production. These systems operate at elevated

temperatures (typically 600–1000°C), which reduces the required electrical energy by utilizing thermal energy.

In SOECs, the electrolyte is typically made of yttria-stabilized zirconia, while the cathode consists of lanthanum oxide doped with metals, and the anode is commonly YSZ doped with nickel (Ni) [31].

I.3.2 Benefits of Producing Hydrogen Through Electrolysers

I.3.2.1 Zero Carbon Emissions

A key advantage of hydrogen production through electrolysis is its ability to produce zero direct carbon emissions. Unlike traditional methods like steam methane reforming (SMR), which rely on natural gas and release significant amounts of carbon dioxide (CO₂), electrolysis requires only water and electricity [32].

$$\text{Renewable Energy} + \text{Electrolysis} = \text{Green Hydrogen}.$$

I.3.2.2 Sustainable Industry

Hydrogen electrolysis is a key technology with the potential to transform industries, promoting greater sustainability and environmental friendliness [33].

I.3.2.3 Electrolysis in Diverse Sectoral Applications

The versatility of green hydrogen is reflected in its wide range of applications across multiple sectors:

- **Transport:** Hydrogen is playing a key role in transforming the transportation sector. It can be used as a fuel for fuel cell vehicles (FCEVs), including cars, buses, and trucks, as well as in trains. Additionally, hydrogen is essential for producing e-fuels such as e-ammonia and e-kerosene, which are vital for decarbonizing shipping and aviation [34].
- **Heating:** Interest is growing in using hydrogen for heating applications. By blending hydrogen with natural gas, or eventually using it on its own, it is possible to significantly reduce carbon emissions from both residential and commercial heating systems [35].
- **In industry,** hydrogen can be used as a feedstock for various chemical processes, helping to reduce dependence on traditional fossil fuels [28].

I.4 Fuel cell

I.4.1 Fuel Cell basic

Fuel cells operate similarly to batteries but do not deplete over time or require recharging [36], A fuel cell produces electricity through an electrochemical reaction rather than combustion [37].

In electrochemical reactions, fuel is delivered to the negative electrodes (anodes) and air to the positive electrodes (cathodes). The reaction between the fuel and the electrodes generates electrons [38].

Each fuel cell contains an electrolyte, which transports electrically charged particles between the electrodes, and a catalyst, which accelerates the reactions at the electrodes [39].

The source of hydrogen is commonly referred to as the fuel, giving the fuel cell its name, even though no combustion occurs. Instead, hydrogen undergoes electrochemical oxidation in a highly efficient process. During this reaction, hydrogen atoms combine with oxygen atoms to form water, releasing electrons that flow through an external circuit as an electric current [40].

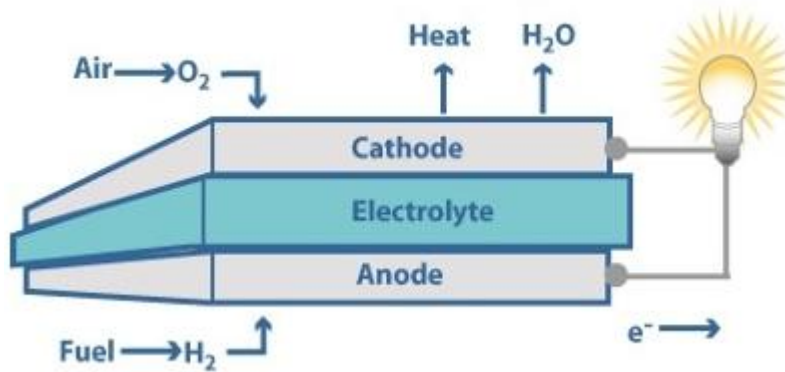


Figure I.1 Fuel Cell Technologies [41]

I.4.2 The fuel cell consideration

The first step in designing a fuel cell stack is to determine the power requirements. Based on these requirements, the stack is engineered to deliver the necessary performance. As a result, the maximum power, voltage, and current of the stack are typically specified during the design process [42].

The power output of a fuel cell stack depends on its size. Increasing the number of cells in the stack raises the voltage, while enlarging the surface area of the cells increases the current. Once assembled, the stack is completed with end plates and connection points to facilitate integration into larger systems [42].

A single fuel cell typically generates between 0.6 and 0.8 volts under load. To achieve higher voltages, multiple cells are connected in series [43].

I.4.3 Fuel cell components

I.4.3.1 Electrodes

An electrode is a conductor that allows electric current to enter or exit a material, whether it's a liquid, solid, gas, or even a vacuum. In a fuel cell, there are two main electrodes [44]:

- Anode: This is where oxidation takes place. In fuel cells, it's also the point where negative ions move toward.
- Cathode: This is where reduction occurs, completing the electrochemical reaction.

I.4.3.2 Electrolyte

An electrolyte is placed between the two electrodes, allowing ions (positively or negatively charged atoms) to pass through while blocking electrons. The electrons are instead directed through an external circuit, generating electricity [45].

I.4.3.3 Gas Diffusion Layers (GDLs)

Are essential components in several types of fuel cells, including Proton Exchange Membrane (PEM), Direct Methanol (DMFC), and Phosphoric Acid (PAFC) fuel cells, as well as in other electrochemical devices like electrolyzers. In a fuel cell, the GDL is a thin, porous sheet that plays several critical roles: it must conduct electricity and heat efficiently, resist chemical corrosion, ensure even distribution of reactant gases (like hydrogen and air), and help manage water removal from the Membrane Electrode Assembly (MEA) [46].

I.4.3.4 Graphite bipolar plates

Crucial components in fuel cells. They connect the electrodes and the electrolyte, while also offering excellent electrical and thermal conductivity. In addition, they help manage gas flow and support the membrane electrode assembly. Essentially, they serve as the backbone and structural foundation of the fuel cell [47].

I.4.3.5 External circuit

When fuel is supplied to the anode side of a fuel cell, it triggers the movement of ions toward the cathode. At the same time, electrons flow through an external circuit to the cathode, creating an electric current that can be used as a power source [48].

I.4.4 Types of fuel cell

Fuel cells come in several types, mainly distinguished by the kind of electrolyte they use to separate the fuel from the oxygen. This difference in electrolyte influences many aspects of how the fuel cell works, including the electrochemical reactions involved, the type of catalyst needed, the operating temperature, and the kind of fuel it requires [49]

	AFC Alkaline	PEMFC Polymer Electrolyte Membrane	DMFC Direct Methanol	PAFC Phosphoric Acid	MCFC Molten Carbonate	SOFC Solid Oxide
Operating temp.(°C)	<100	60-120	60-120	160-220	600-800	800-1000 Low temperature (500-600) possible
Electrolyte	KOH	Perfluoro sulfonic acid (Nafion membrane)	Perfluoro sulfonic acid (Nafion membrane)	H ₃ PO ₄ immobilized in SiC matrix	Li ₂ CO ₃ -K ₂ CO ₃ eutectic mixture immobilized in □-LiAlO ₂	YSZ (yttria stabilized zirconia)
Charge carrier in the electrolyte	OH ⁻	H ⁺	H ⁺	H ⁺	CO ₃ ⁻²	O ²⁻
Anode reaction	H ₂ + 2OH ⁻ → 2H ₂ O + 2e ⁻	H ₂ → 2H ⁺ + 2e ⁻	CH ₃ OH + H ₂ O → CO ₂ + 6H ⁺ + 6e ⁻	H ₂ → 2H ⁺ + 2e ⁻	H ₂ + CO ₃ ²⁻ → H ₂ O + CO ₂ + 2e ⁻	H ² + O ²⁻ → H ₂ O + 2e ⁻
Cathode reaction	½O ₂ + H ₂ O + 2e ⁻ → 2OH ⁻	½O ₂ + 2H ⁺ + 2e ⁻ → H ₂ O	3/2 O ₂ + 6H ⁺ + 6e ⁻ → 3H ₂ O	½O ₂ + 2H ⁺ + 2e ⁻ → H ₂ O	½O ₂ + CO ₂ + 2e ⁻ → CO ₃ ²⁻	½O ₂ + 2e ⁻ → O ²⁻
Electrode materials	Anode: Ni Cathode : Ag	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Pt, PtRu Cathode: Pt	Anode: Ni-5Cr Cathode: NiO(Li)	Anode: Ni-YSZ Cathode: lanthanum strontium manganite (LSM)
Applications	Transportation Space, Military Energy storage systems			Combined heat and power for decentralized stationary power systems	Combined heat and power for stationary decentralized systems and for transportation (trains, boats, ...)	
Realised Power	Small plants 5-150 kW modular	Small plants 5-250 kW modular	Small plants <5 kW	Small-medium sized plants 50 kW-11 MW	Small power plants 100 kW-2 MW	Small power plants 100-250 kW

Table I.1: The Different Fuel Cells that have been Realized and are Currently in Use and Development [50]

I.4.5 Advantages of fuel cell technology

Fuel cells are more efficient than traditional combustion engines because they convert the chemical energy in fuel directly into electricity. This process can reach efficiencies of over 60% [51].

Fuel cells don't produce any harmful pollutants, making them a much cleaner alternative to traditional energy sources [52].

Fuel cells have no moving parts, which means they operate completely silently. While this might not be a big advantage for cars, it can be a real benefit in other settings for example, having a quiet boiler is especially useful for people who have one installed in or near their bedroom [53].

I.4.6 Disadvantages of fuel cell

Despite their advantages, fuel cells also face several challenges:

- ❖ Although hydrogen is the most abundant element in the universe, it doesn't exist in its pure form naturally. To use it as a fuel, it must be extracted either by splitting water through electrolysis or by separating it from fossil fuels that contain carbon. Both methods require a considerable amount of energy to carry out [54].
- ❖ Catalyst materials used in fuel cells are often rare and expensive, which makes them a significant challenge for large-scale adoption [55].
- ❖ Fuel cells and electric motors generally have a shorter lifespan compared to petrol or diesel engines, making them less durable in the long run [56].

I.5 SOFC

I.5.1 History

The journey toward the discovery of galvanic solid electrolyte gas cells began with J.-M. Gaugain in 1853 and eventually led to the first industrial production of such cells with the introduction of Nernst lamps in 1897. The foundational work on solid electrolyte fuel cells was further developed through key contributions by Haber in 1905, Schottky in 1935, Baur in 1937, and Wagner in 1943 [57].

Solid oxide and molten carbonate fuel cells are both high-temperature technologies, and their early development followed similar research paths up until the late 1950s [58].

In the United States, Ruka and other researchers from Westinghouse Electric Corporation published a landmark paper titled "*A Solid Electrolyte Fuel Cell*" in 1962, which laid the foundation for Westinghouse's cathode-supported tubular SOFC design. Building on this work, the company

successfully tested SOFC power systems ranging from 5 to 250 kW between the late 1980s and early 2000s [59].

Between 1987 and 1997, Osaka Gas, in collaboration with Tokyo Gas Co., Ltd. and the U.S. company Westinghouse (WH), worked on evaluating SOFC power generation systems and developing cogeneration systems. A notable milestone was a 3,000-hour test of a 3kW tubular cell module conducted in 1987, which played a key role in sparking numerous SOFC research and development initiatives across Japan by the early 1990s [60].

I.5.2 The choice of SOFC

The SOFC offer several advantages over first-generation phosphoric acid fuel cells (PAFCs) and second-generation molten carbonate fuel cells (MCFCs):

I.5.2.1 Higher performance

To maximize the overall energy efficiency of the power plant, heat recovery systems-such as heat exchangers-should be integrated into the system layout [61].

I.5.2.2 Fuel flexibility

SOFCs offer the flexibility to operate on a wide range of fuels, including hydrogen, Liquefied Natural Gas, biogas, methanol, ammonia, and e-fuels. While LNG is currently the most widely used fuel in many applications, it is not considered a sustainable long-term solution due to methane emissions and the high energy demands of its liquefaction and regasification processes [62].

I.5.2.3 High energy efficiency

Solid oxide fuel cell cogeneration systems, known for their high energy efficiency and low emissions, represent a promising solution for generating both electricity and heat in future residential buildings [63].

I.5.3 SOFC Basic

The basic structure of a solid oxide fuel cell includes a solid ceramic electrolyte sandwiched between an anode and a cathode. Fuel is supplied to the anode, while air, serving as the oxidant, is delivered to the cathode [64].

A single fuel cell is made up of three main components: an anode, a cathode, and an electrolyte that separates them. Bipolar plates on either side of the cell help distribute the gases and act as current

collectors[65]. This is the anodic oxidation(I.3), the cathodic reduction(I.4) and the overall cell reaction(I.5) [66]:

✓ At the anode of SOFC:



✓ The reduction of oxygen in cathode is given by:



✓ The overall cell reaction is:

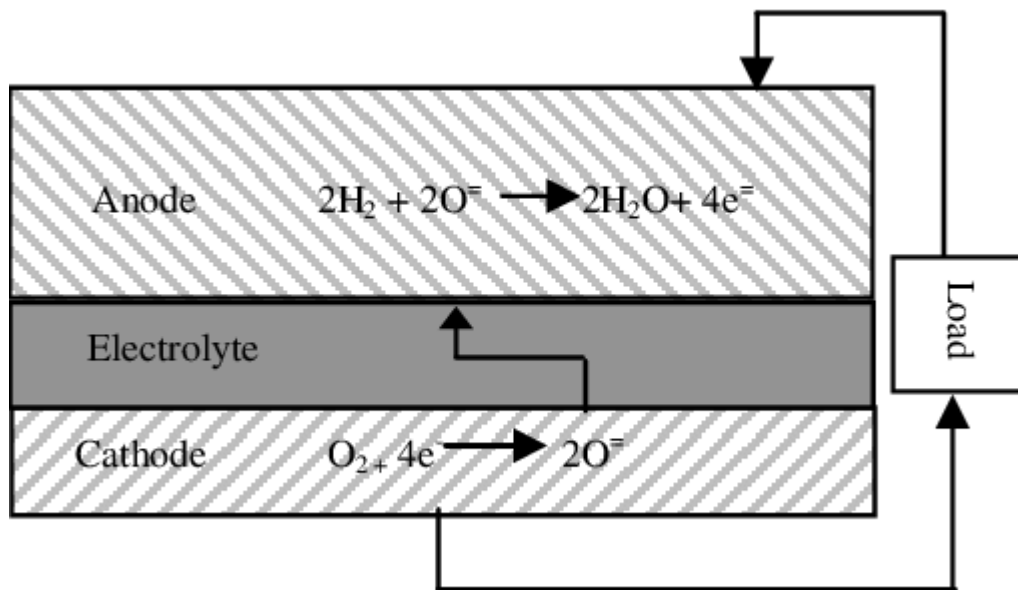


Figure I.2: Governing electrochemical reactions for a solid oxide fuel [67]

I.5.5 Cogeneration

SOFC stacks are primarily designed for cogeneration. The heat they produce can be recovered using heat exchangers for domestic heating. When there is no heat demand, this thermal energy can also be redirected to a steam turbine to generate more electricity [68].

I.5.6 SOFC Structure

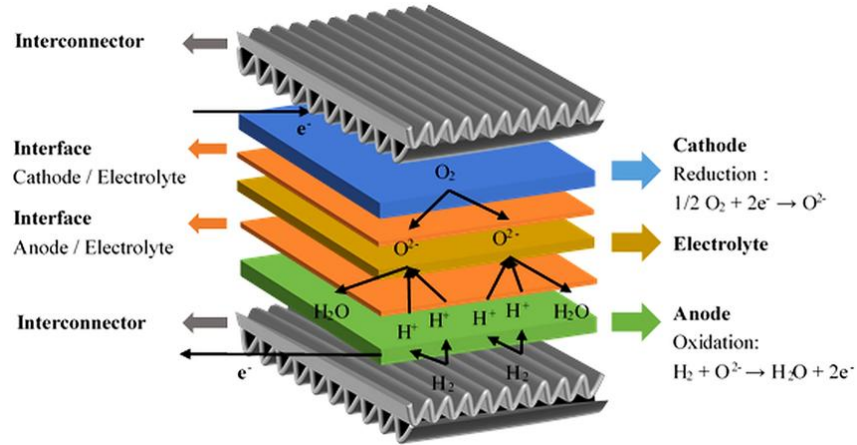


Figure I.3: Basic structure of Solid oxide fuel cell [69]

I.5.6.1 Electrolytes

In SOFCs, a dense ceramic electrolyte is used, designed to conduct oxygen ions (O^{2-}) while minimizing or eliminating electronic conduction in order to reduce current leakage[70]. The main role of the electrolyte is to transport oxygen ions within the fuel cell [71].

I.5.6.2 Cathode

The cathode plays a critical role in cell performance, as it is the site of the oxygen reduction reaction (ORR). Since electrons are required for this reaction, a key requirement for the cathode material is high electronic conductivity [72].

I.5.6.3 Anode

At the anode, the fuel undergoes oxidation, which is a key part of the electrochemical process in SOFCs [73].

I.5.6.4 Mathematical model

At a basic level, when a fuel cell is connected to an external load, the potential difference between the electrodes drives electrons through the external circuit, generating an electric current.

The voltage cell is determine [74]

$$V_{cell} = V_{Nernst} - \eta_{ohm} - \eta_{act} - \eta_{dif} \quad (I.6)$$

V_{cell} is the cell voltage

η_{ohm} is the ohmic polarization

$V_{Nernestl}$ is the Nernest potential

η_{act} is the activation

η_{dif} is the diffusion polarization

I.5.7 Chemical reaction

This study refers to the article [75]

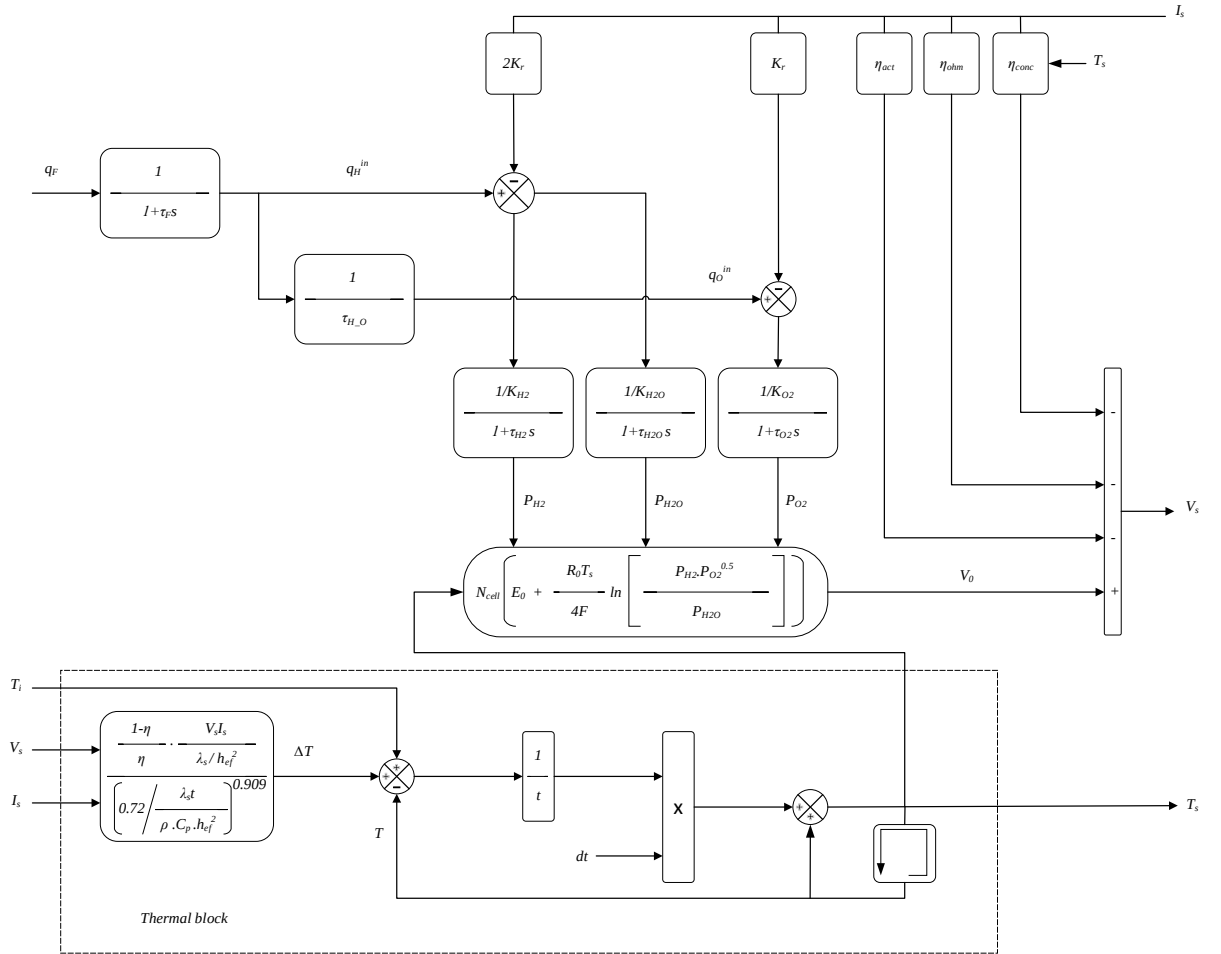


Figure I.4: Block diagram of the thermal block of the SOFC

Parameter	Representation	Value	Parameter	Representation	Value
K_r	Reaction constant	0.993×10^{-3} mol/(s A)	E_{act}	Activation energy	120 kJ/mol
K_{H_2}	Valve molar constant for hydrogen	0.843 mol/(s atm)	A	Pre exponential factor	101.2 kA/cm ²
K_{H_2O}	Valve molar constant for steam	0.281 mol/(s atm)	A	Ohmic resistance constant	0.2 Ω
K_{O_2}	Valve molar constant for oxygen	2.52 mol/(s atm)	B	Ohmic resistance constant	-2870 K
τ_{H_2}	Response time for hydrogen flow	26.1 s	T_0	Constant temperature	973 K
τ_{H_2O}	Response time for steam flow	78.3 s	H	Efficiency	0.8
τ_{O_2}	Response time for oxygen flow	2.91 s	h_{eff}	Thickness	10^{-3} m
τ_F	Fuel processor response time	5 s	Λ_s	Thermal conductivity	2 W/(m K)
F	Faraday's constant	96,486 C/mol	T	Relaxation time	200 s
R	Gas constant	8.31 J/(mol K)	P	Density	6600 kg/m ³

E_0	Ideal standard potential	1.1 V	Cp	Heat capacity	400 J/(kg K)
N	Number of cells in stack	384	T_{int}	Initial temperature	1273 K

Table I.2: Nominal parameters of SOFC system

Electrochemical relationships can be used to estimate the partial pressures as follows:

$$P_{H_2} = \frac{1}{K_{H_2} (1 + \tau_{H_2} s)} \left(\frac{1}{1 + \tau_F s} q_F - 2K_r I_s \right) \quad (I.7)$$

$$P_{O_2} = \frac{1}{K_{O_2} (1 + \tau_{O_2} s)} \left(\frac{1}{\tau_{H-O} (1 + \tau_F s)} q_F - K_r I_s \right) \quad (I.8)$$

$$P_{H_2O} = \frac{2}{K_{H_2O} (1 + \tau_{H_2O} s)} K_r I_s \quad (I.9)$$

Here, K_r denotes a reaction constant in units of mol/(s.A), and it is defined by equation (I.10):

$$K_r = \frac{N_{cell}}{4F} \quad (I.10)$$

- N_{cell} : is the number of cells in the stack.
- E_0 : is the ideal standard potential in unit of V.
- R_0 : is the universal gas constant equal to 8.314 J/(mol.K).
- T_s : is the operating temperature in unit of K.
- F : is the Faraday's constant equal to 96.486 coulombs C/mol.

- $K_{H_2}, K_{O_2}, K_{H_2O}$: are the valve molar constant for hydrogen, oxygen, and water, respectively, in unit of mol/(s.Pa).
- $\tau_{H_2}, \tau_{O_2}, \tau_{H_2O}$: are the response time of hydrogen, oxygen, and water flows, respectively, in unit of s.
- τ_{H-O} : is the response time between the hydrogen and oxygen flows in unit of s.
- τ_F : is the time constant of fuel processor in unit of s.
- q_F : is the fuel flow rate in unit of mol/s.
- I_s : is the external load current in unit of A.

The output voltage can be calculated by taking into account the activation loss, concentration loss, and ohmic loss, as follows:

$$V_{fc} = V_0 - V_{act} - V_{ohm} - V_{conc} \quad (I.11)$$

Here, V_{fc} (in volts) represents the output voltage of the SOFC, while V_{act} , V_{ohm} , and V_{conc} denote the activation loss, ohmic loss, and concentration loss, respectively. These voltage losses can be expressed as functions of temperature using the following equations:

$$V_{act} = \frac{RT}{F} \left(z + \sqrt{1 + z^2} \right) \quad (I.12)$$

$$z = I_{fc} / 2I_0$$

$$I_0 = A \cdot \exp \left(-E_{act} / RT \right) \quad (I.13)$$

$$V_{ohm} = \alpha \cdot \exp \left[\beta \left(\frac{1}{T_0} - \frac{1}{T} \right) \right] I_{fc} \quad (I.14)$$

$$V_{conc} = \frac{RT}{2F} \ln \left(1 - \frac{I_{fc}}{i_L} \right) \quad (I.15)$$

The Fourier number (Fo) and the source term number (S_o) are the two key parameters used to express the thermal equations in a dimensionless form. They are defined as follows:

$$F_0 = \frac{\lambda_s t}{(\rho c_p) h_{eff}^2} \quad (I.16)$$

$$S_0 = \frac{1-\eta}{\eta} \cdot \frac{V_{fc} I_{fc}}{\lambda_s \Delta T / h_{eff}} \quad (I.17)$$

Here, t (in seconds) represents the relaxation time, which is the time required for the system to reach 90% of its new steady-state value. T (in °C) denotes the temperature change during this relaxation period. The relationship between the Fourier number (Fo) and the source term number (S_o) can be expressed as follows:

$$F_0 = 0.72 S_0^{-1.1} \quad (I.18)$$

Based on Equations (9) to (11), the expression for T_{out} can be rewritten as follows:

$$T_{out} = T + \left(\frac{T_{int} + \Delta T - T}{t} \right) dt \quad (I.19)$$

Here, T (in °C) is the current temperature of the fuel cell, T_{int} (in °C) is the initial temperature when no load is applied, and dt represents the simulation time step in Simulink.

The fuel utilization factor u_f is another important indicator for SOFC performance. It reflects the proportion of the fuel that actually reacts compared to the total fuel input:

$$u_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{2K_r I_{fc}}{q_{H_2}^{in}} \quad (I.20)$$

$q_{H_2}^{in}$ is the fuel flow entering the system, and it represents the output portion of the fuel flow. Typically, u_f is maintained within the range of 0.7 to 0.9 to ensure high efficiency and safe operation.

I.5.8 Open-Circuit EMF of a Fuel Cell Stack

- **Ideal stack voltage**

By applying Nernst's law to equation (I.21), we derive the expression for the ideal stack voltage under the given operating conditions, as follows equation:

$$V_0 = N_{cell} + \left(E_0 + \frac{R_0 T_s}{4F} \ln \left[\frac{P_{H_2} \cdot P_{O_2}^{0.5}}{P_{H_2O}} \right] \right) \quad (I.21)$$

I.5.9 Types of losses

The SOFC experiences three main types of losses [76]:

- **ohmic losses:**

$$\eta_{ohm} = r I_s \quad (I.22)$$

Since r it represents the cell's total resistance in unit of Ω , it can be expressed as equation (I.23):

$$r = r_0 \exp \left[\alpha \left(\frac{1}{T_0} - \frac{1}{T_s} \right) \right] \quad (I.23)$$

- r_0 : is the cell's internal resistance at temperature T_0 in unit of Ω .g
- α : is a constant.
- T_0 : is a constant temperature in unit of K .

- **activation losses**

$$\eta_{act} = \varnothing + \beta \log I_s \quad (I.24)$$

- $\varnothing$: is the Tafel's constant.
- β : is the Tafel slope.

- **Concentration losses**

$$\eta_{conc} = \frac{R_0 T_0}{2F} \ln \left[1 - \frac{I_s}{I_l} \right] \quad (I.25)$$

- Where, I_l : is the limiting current density in unit of A .

Ohmic polarization results from several resistive factors, including the ionic resistance of the electrolyte, the electrical resistance of the electrodes, the resistance in the cell interconnects, and the contact resistance between these components [77].

I.6 Conclusion

This chapter provided a comprehensive overview of the fundamental concepts related to hydrogen, its production through electrolysis, various fuel cell technologies, with a particular focus on SOFCs.

Hydrogen, as a clean and abundant energy carrier, offers a promising solution to current and future energy challenges. Its production via water electrolysis is a sustainable method, especially when coupled with renewable energy sources, ensuring a low environmental impact energy cycle.

Fuel cells, which directly convert the chemical energy of hydrogen into electricity, represent a key technology for clean energy production, with diverse applications ranging from transportation to stationary power generation. Among these technologies, SOFCs stand out due to their high efficiency, fuel flexibility, and ability to operate at high temperatures, which gives them significant potential in modern energy systems.

However, despite their many advantages, SOFCs still face technical challenges, particularly related to material durability and thermal management. These issues require ongoing research to improve the performance, reliability, and economic viability of this technology.

Therefore, this chapter lays the essential foundation for a deeper understanding of SOFC systems and directs attention to the control and optimization of fuel and oxygen flows, which will be explored in the subsequent chapters.

Chapter II

PID controller, Fuzzy Logic Control type one and two

II.1 Introduction

In the field of dynamic system control, selecting the appropriate control strategy is essential to ensure system stability, performance, and robustness against uncertainties and disturbances. This chapter explores and compares three fundamental control approaches: the classical PID controller, Type-1 fuzzy logic systems, and Type-2 fuzzy logic systems.

The PID controller is widely used in industry due to its simplicity and effectiveness in systems with well-defined and linear dynamics. However, its performance often degrades in the presence of nonlinearities or uncertain environments. To address such limitations, T1-FLC introduces rule-based reasoning and linguistic variables, providing greater flexibility and adaptability in handling vague or imprecise information.

Despite its advantages, T1-FLC may still struggle under high uncertainty. To overcome this, T2-FLC offer an enhanced framework by incorporating a higher degree of uncertainty into their membership functions. This makes them particularly suitable for complex, noisy, or highly dynamic systems.

This chapter provides a detailed analysis of these three control strategies, discussing their theoretical foundations, architectures, strengths and limitations, and practical applications. The goal is to establish a clear comparative understanding to support the selection of the most appropriate controller for advanced systems such as SOFCs or hybrid energy systems.

II.2 PID controller

A PID controller is a widely used instrument in industrial control systems. It helps control engineers regulate key process variables such as temperature, flow, pressure, and speed. By using a feedback control loop, the PID controller continuously monitors and adjusts the system output to maintain the desired setpoint.

Thanks to its structure-which combines proportional, integral, and derivative actions-the PID controller is known for delivering high accuracy and stable performance, making it one of the most reliable control strategies in modern automation [78].

II.2.1 Components of a PID Loop

A PID controller consists of three key components:

- **Proportional Control (P):** Proportional control is a technology that involves a control system where the reaction is in direct proportion to the difference between the set-point and the actual value [79].
- **Integral Control (I):** Integral control is an important aspect of a control system whereby error is integrated over time and corrective action is taken. In engineering, an integral control is an important term that ensures system performance. It is a major part of PID control systems which are widely used in the industry [80].
- **Derivative Control (D):** A derivative controller monitors how quickly the error between the setpoint and process variable is changing over time. The output signal from a derivative controller corresponds to the rate of change or the slope of the error [81].

By combining these three components, a PID controller ensures smooth and efficient process regulation across various industrial applications.

II.2.2 Control parameters

A PID controller consists of three key components: Proportional, Integral, and Derivative. However, not all of them are used in every application, it depends on the system's requirements.

In simple terms, the controller calculates the P, I, and D actions based on the error value, which is the difference between the setpoint (SP) and the process variable (PV), assuming a direct-acting setup. Each component is multiplied by this error, and the results are then summed to generate the final control output, known as the Control Variable [82].

The process described above can be summarized using the following formula [83]:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (\text{II.1})$$

where:

- $u(t)$ is the drive coming from the Controller, into the Process, at time t .
- $e(t) = y_{sp}(t) - y(t)$ is the difference between the setpoint and measured process variable at time t .
- k_p, k_i, k_d are the respective P , I , and D constants.

The figure(II.1) below explain the block diagram of the PID controller [84]:

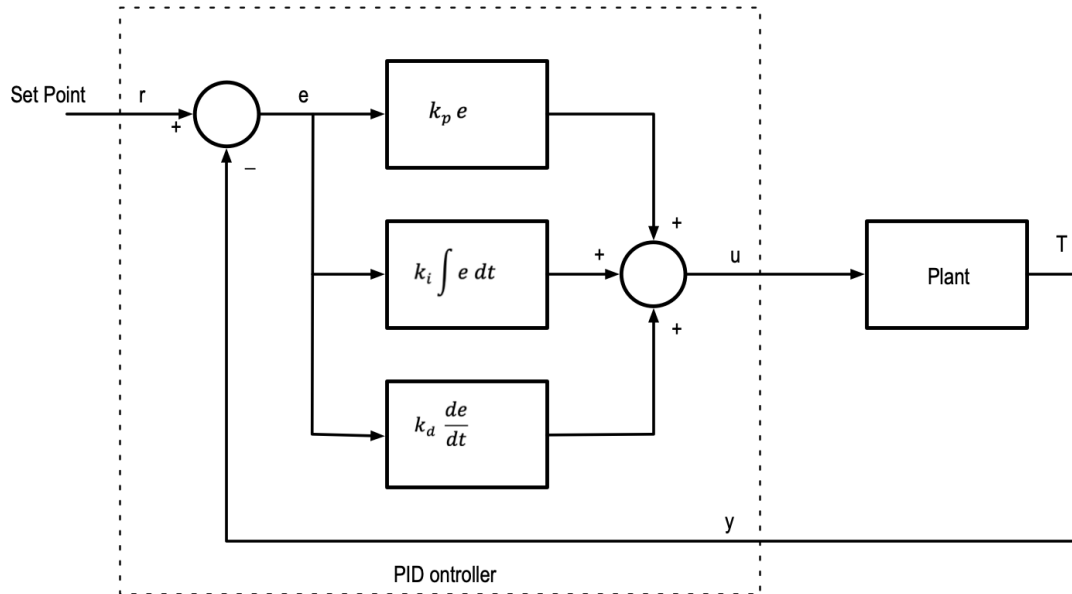


Figure II.1: The block diagram of the PID controller

II.2.3 Types of PID controller

PID controllers are classified into three types like ON/OFF, proportional, and standard type controllers. These controllers are used based on the control system, the user can be used the controller to regulate the method.

- ON/OFF Control:** An on-off PID controller is the simplest type of temperature control device. It operates with just two output states-either fully on or fully off-without any in-between levels. The controller activates or deactivates the output only when the temperature crosses a defined setpoint.
 A special variation of this is the limit controller, which uses a latching relay that must be manually reset. This type is typically used to shut down a process once a specific temperature threshold is reached, providing an added layer of safety [85].
- Proportional Control:** Proportional control is a system where the output response is directly related to the difference between the desired setpoint and the actual value of a process variable. In simple terms, the greater the difference, the stronger the response-helping the system adjust smoothly and efficiently toward the target value [86].
- Standard Type PID Controller:** This type of PID controller combines proportional control with integral and derivative actions to automatically help the system adapt to changes. The integral and derivative components respond to variations over time, allowing the controller to make more accurate and stable adjustments [87].

II.2.4 Main applications of PID controllers

PID controllers play a crucial role in closed-loop systems where precise process control is essential. Their versatility allows them to be implemented in various industries and applications, including:

- **Home Heating and Cooling Systems:** PID controllers are becoming increasingly popular at home heating and cooling systems because they improve energy efficiency while maintaining comfortable living conditions. By precisely managing temperature settings, these controllers help create an optimal indoor environment for residents. At the same time, they significantly reduce energy consumption and lower energy costs [88].
- **Industrial Automation:** The PID controller has become the standard for process control applications in various industries, including manufacturing, chemical, automotive, and aerospace [89].
- **Robotics and Motion Control:** A PID controller is a basic control algorithm which is used in robotics for adjusting an output depending on the difference between a setpoint and current state of the robot [90].
- **Process Control Applications:** PID controllers are commonly used for process control applications like chemical processing, power generation, and manufacturing operations [89].
- **Automatic Machine Control:** PID controllers also play a key role in automatic machine control systems. They are commonly used in processes such as production counting, cutting, and other precision-based tasks, ensuring accuracy and efficiency in industrial operations [87].
- **Renewable Energy Systems:** PID controllers optimize energy capture and voltage regulation in solar power systems and wind turbines, enhancing efficiency [91].

PID controllers are widely used across industries due to their reliability and effectiveness in maintaining system stability and optimizing performance

II.2.5 Advantages and disadvantages of PID Control

The PID algorithm is a versatile and widely used control technique applicable to various processes, provided the process variable can be adjusted to match the desired value over time.

Advantages of PID controllers

- **Simplicity:** PID controllers are easy to understand and implement, making them ideal for both beginners and experienced engineers [92].

- **Higher Accuracy:** One of the primary benefits of digital PID controllers is the improved accuracy and precision. Microprocessors are employed in digital controllers for the purpose of calculation, making it possible to fine-tune the system [93].
- **Energy Efficiency:** The PID control's capacity to tweak the output based on how the error's rate of change (derivative part) allows for speedy, as well as precise response, which in turn lowers power consumption [94].

Disadvantages of PID controllers

- **Potential for Instability:** PID impacts can result in substantial power reduction, estimated to be as high as 20%, and the result does not become immediately evident - the results of the impact may take a few months to a few years to show up [95].
- **Noise Amplification:** In control systems, we often find noises that are random or unwanted fluctuations in the measured signal but changes that do not indicate any process. When such a signal is given as input to a PID controller, it can result in undesirable and unstable control [96].
- **Challenges with Long Delays:** The system does not respond instantly to changes, so there is a delay between the controller's action and the change in process variable [97].

While PID controllers remain a fundamental and reliable control solution, they may require augmentation with additional intelligence in complex applications.

II.3 Fuzzy logic type1

II.3.1 Definition

A Type-1 Fuzzy Logic System is a core concept in fuzzy logic, designed to handle uncertainty and imprecision in a structured, mathematical way. It uses fuzzy sets with precise membership functions to model vague or ambiguous information, making it especially useful for complex systems where traditional binary logic falls short [98].

II.3.2 General operation of fuzzy logic

Fuzzy logic enables reasoning with values that fall between absolute truth and absolute falsehood. Unlike classical logic, which limits truth values to either 0 or 1, fuzzy logic assigns values within the continuous range of 0.0 to 1.0, representing varying degrees of truth. This approach allows for a more nuanced evaluation of how strongly an element belongs to a specific set, making it especially useful in systems that deal with uncertainty, imprecision, or complex decision-making [99].

II.3.3 Architecture

The architecture of a T1-FLC is composed of four main components:

II.3.3.1 Fuzzification interface

The fuzzification interface is the first step in the processing of a fuzzy logic system. Its role is to convert precise numerical values (non-fuzzy) from the real world into fuzzy sets. To do this, it uses an operator called a fuzzifier, which assigns a membership function $\mu_{x_0}(x)$ to each input value x_0 . This function represents the degree to which x_0 belongs to a given fuzzy set, thereby enabling the application of fuzzy rules in the next step of the process [100].

II.3.3.2 Rule base

This component holds a collection of IF-THEN rules formulated using expert knowledge and linguistic variables. These rules guide the system's decision-making process. Recent advancements in fuzzy theory have introduced efficient methods for designing and optimizing fuzzy controllers, often reducing the number of rules needed without compromising performance [101].

II.3.3.3 Fuzzy inference engine

The fuzzy inference engine is the core of the fuzzy logic system. It uses the IF-THEN rules stored in the knowledge base to perform logical reasoning. Based on the fuzzy inputs provided by the fuzzifier, it processes the information and generates a fuzzy output, which will later be converted into a crisp value during the defuzzification stage [102].

II.3.3.4 Defuzzification methods

Fuzzy rule-based systems work by evaluating linguistic IF-THEN rules through the steps of fuzzification, inference, and composition. These steps result in a fuzzy output, which typically needs to be converted into a precise, actionable value. This conversion is carried out through a process called defuzzification.

Defuzzification is the method used to transform a fuzzy output into a single crisp value, based on the associated fuzzy set. In a FLC, the defuzzified value represents the final control action to be applied to the system or process being managed [103].

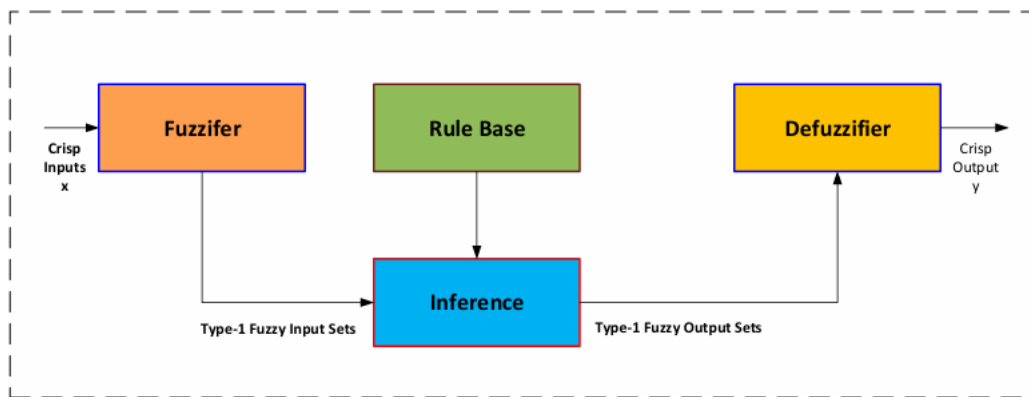


Figure II.2: Fuzzy logic type 1 [104]

II.2.4 Types of fuzzy inference system

II.2.4.1 Mamdani Fuzzy Inference System

The Mamdani model, introduced by Dr. Ebrahim Mamdani in 1975, is one of the earliest and most widely used types of fuzzy [105]:

Key Characteristics

- **Fuzzy Output Rules:** Each fuzzy rule generates an output in the form of a fuzzy set rather than a single numeric value.
- **Defuzzification Required:** Since the outputs are fuzzy sets, a defuzzification step is necessary to convert the result into a crisp value. The centroid method is most commonly used for this.

II.3.4.2 Sugeno fuzzy inference system

Also known as the Takagi-Sugeno-Kang (TSK) model, the Sugeno fuzzy inference system was introduced in 1985. While it shares many similarities with the Mamdani method-particularly in the early steps of the process-it has some key differences that make it more suitable for certain applications.

Key Characteristics

- **Same Initial Steps:** Like the Mamdani method, the Sugeno approach starts by fuzzifying the inputs and then applying fuzzy operators to evaluate the rules.

- **Different Output Structure:** The main distinction lies in the output. Instead of fuzzy sets, the Sugeno method uses mathematical functions (usually linear or constant) as outputs of the rules.
- **No Need for Defuzzification:** Since the output is already a crisp value (not a fuzzy set), there's no need for a separate defuzzification step. This makes the Sugeno system computationally more efficient.

This second type of fuzzy logic control [106].

II.3.5 Advantages of Fuzzy Logic

- Fuzzy logic is based on human-like reasoning and intuitive logic sets, making it easy to understand and interpret.
- It is user-friendly, allowing engineers and operators to work with it without requiring deep mathematical background.
- Fuzzy logic can effectively solve complex, nonlinear problems that are difficult or impossible to model using traditional mathematical approaches.
- It delivers reliable and accurate results even when input data is uncertain, imprecise, or noisy.
- Due to its flexibility and robustness, fuzzy logic is widely adopted in practical and commercial applications across various industries, including automation, control systems, and consumer electronics [107].

II.4 Fuzzy logic type 2

II.4.1 Definition

Type-2 fuzzy sets, first introduced by Zadeh in 1975, are an extension of traditional fuzzy sets designed to model uncertainty and imprecision more effectively. Unlike type-1 fuzzy sets, in type-2 fuzzy sets, the degree of membership itself is a fuzzy set-hence, they are often described as "fuzzy fuzzy" sets [108].

Basically, an interval type-2 fuzzy system uses interval type-2 fuzzy sets, where the secondary membership degree is assumed to be constant. This simplifies the process by avoiding the need to evaluate multiple membership degrees [109].

Type-2 fuzzy logic systems provide a way to handle levels of uncertainty that traditional type-1 fuzzy logic struggles to represent. By adding an extra dimension, they offer more flexibility and greater freedom to model uncertainty more accurately than type-1 fuzzy sets [110].

II.4.2 Principles of fuzzy logic type2

We introduce a type-2 fuzzy logic system (FLS) capable of handling uncertainty within the rule base. Its implementation involves the standard stages of fuzzification, inference, and output processing. In this work, we place particular emphasis on the output processing stage, which includes two key steps: type-reduction and defuzzification [111].

The figure(II.3) of fuzzy logic type-2 explain the architecture [112]:

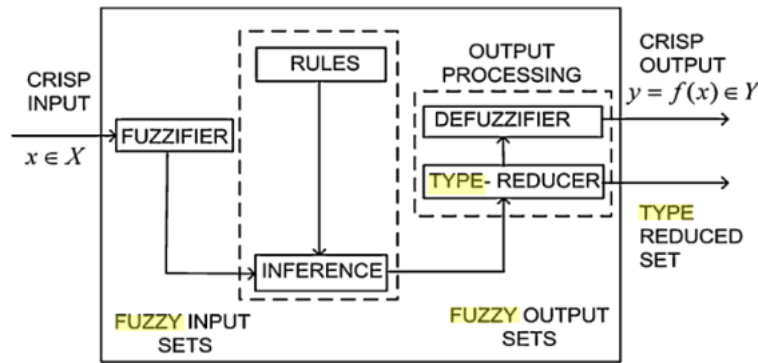


Figure II.3: Fuzzy logic system type2

II.4.3 Type-2 Fuzzy inference systems (T2-FIS)

A Type-2 Fuzzy Inference System is an extension of the traditional Type-1 system, specifically designed to handle higher levels of uncertainty and imprecision in real-world data [113].

Here's how a T2-FIS works, structured around its main components:

II.4.3.1 Fuzzification

The system first converts crisp input values into fuzzy sets. Unlike Type-1 systems, the resulting fuzzy sets in T2FIS include an added layer of uncertainty-meaning the membership values themselves can vary within a range [112].

II.4.3.1 classification rules

Are built by extending traditional type-1 rules. In this case, type-1 fuzzy sets are simply replaced with type-2 fuzzy sets.

For a classification problem with M classes, a typical type-2 fuzzy rule is written as:

R_j: If x is $\tilde{A}_j$, then $(r_1^j, \dots, r_M^j)$

Where:

- $\tilde{A}_j$ is a type-2 fuzzy set,
- $(r_1^j, \dots, r_M^j)$ represent the degrees of support or confidence for each of the M classes.

This rule structure helps better manage uncertainty in classification and decision-making systems [112].

- Inference Engine:

The inference engine of a type-2 fuzzy system consists of a central rule base and identical upper and lower t-norm function blocks that handle fuzzy inference [114].

- Defuzzification:

The final step involves converting the fuzzy output back into a single crisp value. In T2FIS, this process accounts for the embedded uncertainties, often through an intermediate type-reduction step, which simplifies Type-2 fuzzy sets into Type-1 before defuzzifying [115].

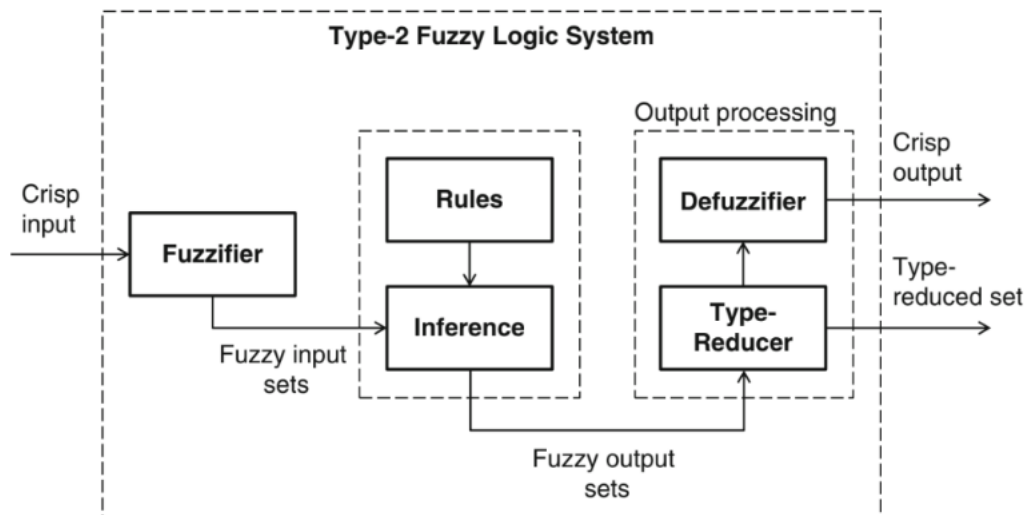


Figure II.4: Structure of type2-FLS [116]

II.4.4 Applications of fuzzy logic domains

- To date, type-2 fuzzy sets and FLSs have been applied in a wide range of fields, including decision making, solving fuzzy relation equations, survey analysis, time-series forecasting, function approximation, time-varying channel equalization, mobile robot control, and data preprocessing [117].
- Type-2 fuzzy logic, combined with traditional soft computing (SC) techniques, has been effectively used to solve pattern recognition problems in real-world applications. In particular, it has been applied to face, fingerprint, and voice recognition. Additionally, it has been used to identify individuals by integrating information from all three biometric sources: face, fingerprint, and voice. Beyond pattern recognition, type-2 fuzzy logic and SC techniques have also been successfully applied in areas such as intelligent control, intelligent manufacturing, and adaptive noise cancellation [118].

II.4.5 Advantages of fuzzy logic type 2

- An extension of traditional type-1 fuzzy logic, type-2 fuzzy logic is particularly well suited for modeling higher levels of imprecision and uncertainty (Mendel, 2000) [119].
- There is growing interest in the research and development of fuzzy systems, particularly those based on type-2 fuzzy logic, because of their advantages in handling uncertainty. As a result, these systems are highly anticipated for use in control applications, where they can help compensate for errors caused by instrumentation and other factors. However, a major drawback is that they require significant computational resources [120].

II.5 Conclusion

This chapter presented the theoretical foundations of three widely used control strategies: the PID controller, the Type-1 fuzzy logic controller, and the Type-2 fuzzy logic controller.

The PID controller is based on mathematical principles that combine proportional, integral, and derivative actions to ensure precise regulation of process variables. Its theoretical basis lies in classical control theory, making it suitable for systems with well-understood dynamics.

The Type-1 fuzzy logic controller is grounded in fuzzy set theory and linguistic rule-based systems. It operates by transforming crisp inputs into fuzzy values, applying inference through IF-THEN rules, and converting the fuzzy output back into a crisp control action. This allows the controller to deal with imprecise or uncertain information in a structured manner.

The Type-2 fuzzy logic controller extends the theory of Type-1 systems by introducing uncertainty directly into the membership functions. Its theoretical framework includes additional steps such as type-reduction and a more complex inference mechanism. This enables it to better represent and manage uncertainties inherent in real-world systems.

Together, these control strategies provide diverse theoretical tools for designing control systems capable of addressing a wide range of challenges, from precise regulation to managing ambiguity and uncertainty.

Chapter III
Simulation results

III.1 Introduction

Solid Oxide Fuel Cells represent a promising technology in the field of clean and efficient energy conversion. Characterized by high operating temperatures, fuel flexibility, and relatively high efficiency, SOFCs are increasingly being explored for stationary power generation and hybrid energy systems. However, the dynamic behavior and nonlinear characteristics of SOFC systems pose significant challenges for efficient control, particularly in the presence of external disturbances, load variations, and parameter uncertainties [64].

To address these challenges, advanced control strategies are essential to ensure stable operation, high efficiency, and fast dynamic response. Among the widely used controllers, the Proportional-Integral-Derivative (PID) controller remains popular due to its simplicity and ease of implementation. However, its performance tends to degrade in highly nonlinear or uncertain environments, such as those encountered in SOFC systems [75].

In contrast, fuzzy logic controllers offer a more robust alternative by incorporating human-like reasoning into control strategies. T1-FLCs use crisp membership functions and provide good control performance in nonlinear systems. However, their ability to handle uncertainties is limited [121]. To overcome this limitation, T2-FLCs have been developed, featuring fuzzy membership functions that can better manage uncertainties and imprecision in system modeling and external disturbances [122].

This study presents a comparative simulation analysis of SOFC dynamic performance under three control approaches: PID, Type-1 FLC, and Type-2 FLC. The aim is to evaluate and compare their effectiveness in managing fuel and oxidant flows, stabilizing cell voltage, and enhancing overall system performance under dynamic operating conditions. Key performance metrics such as Integral of ITAE, rise time, settling time, and steady-state error are used to quantitatively assess each controller's performance.

Through MATLAB/Simulink simulations, this work provides insights into the advantages and limitations of traditional and intelligent control strategies for SOFCs, guiding future development toward more robust and adaptive control systems for fuel cell technologies.

III.2 The parameters of SOFC

Maximum output voltage: 312.4V

Number of cells: 384 cells

U_{cell} : 0.8V

III.3 Control SOFC with PID controller

Controlling a SOFC system with a PID controller is a classical and widely studied approach to manage the dynamic behavior of the cell, particularly in regulating output voltage, temperature, and the fuel/oxidant flow rates.

In this study we can show the output voltage of SOFC With reference value of voltage egal 305V.

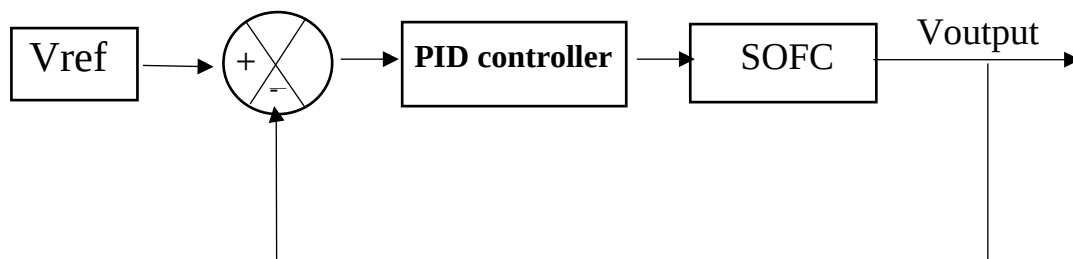


Figure III.1: Control SOFC by PID Controller

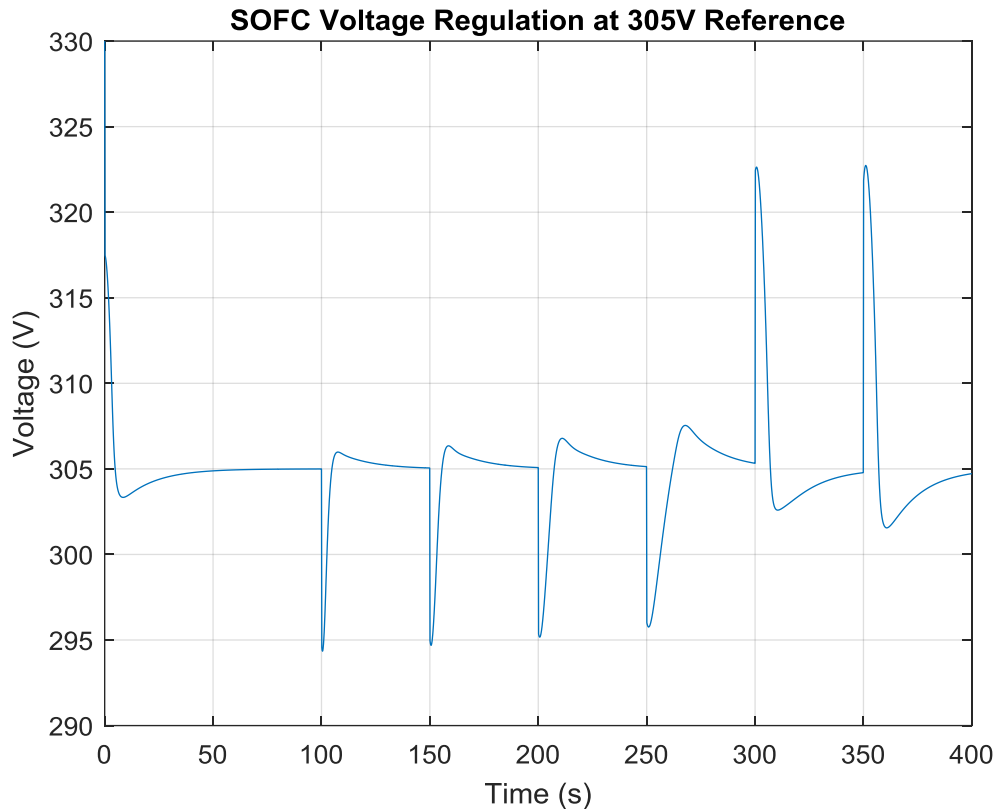


Figure III.2: control voltage with PID Control

➤ Implementation:

- ❖ The controller attempts to regulate the voltage at 305 V.
- ❖ There are repeated voltage dips and spikes throughout the timeline.
- ❖ The system exhibits oscillatory behavior and instability during disturbances.
- ❖ Initial Response (0 to ~30s):
 - The voltage drops sharply at the start but quickly stabilizes around the reference value of 305 V.
 - This indicates a fast initial response of the PID controller.
- ❖ Periodic Disturbances (~100s, 150s, 200s, etc.):
 - Sudden voltage dips below 295 V occur multiple times, suggesting external disturbances or load changes.
 - The PID controller recovers from these dips but not very smoothly-it shows overshoots and ringing after each disturbance.
- ❖ Late-Stage Spikes (~300s, 350s):
 - Larger voltage spikes up to 325 V appear, followed by oscillations.

- This may indicate the controller is not well-tuned to handle strong disturbances or rapid dynamic changes.
- The overshoot is more pronounced and slower to settle, suggesting insufficient damping and possibly aggressive derivative or integral action.
- **Steady-State Behavior:**
 - Between disturbances, the voltage remains close to 305 V, but never perfectly steady.
 - Shows small fluctuations, indicating steady-state error is minimal but not zero.

III.4 Fuzzy Logic Type1

Solid Oxide Fuel Cells are promising energy conversion devices known for their high efficiency, fuel flexibility, and low emissions. However, their dynamic behavior is inherently nonlinear and sensitive to disturbances such as load variations, fuel supply changes, and thermal fluctuations[123]. These characteristics pose significant challenges to conventional linear control methods like PID, particularly in maintaining stable output voltage around a desired reference, such as 305 V, under varying operating conditions.

To address these challenges, T1-1FLC offers a robust and flexible alternative. Unlike conventional controllers that require precise mathematical models, Type-1 FLC relies on linguistic rules and fuzzy inference to handle system uncertainties and nonlinearities. In this approach, expert knowledge is embedded into a set of IF-THEN rules, and the controller adjusts system inputs based on fuzzy reasoning rather than fixed gain calculations.

In the context of SOFC voltage regulation, a Type-1 FLC monitors the error between the desired voltage (305 V) and the actual voltage, as well as the change in error, to generate control actions for regulating fuel and oxidant flows or other relevant inputs. This allows the system to adaptively respond to disturbances and maintain voltage stability more effectively than traditional PID controllers.

This study focuses on implementing and simulating a Type-1 fuzzy logic controller in MATLAB/Simulink for regulating the SOFC output voltage at 305 V, and evaluates its performance under various dynamic scenarios. The objective is to assess the controller's ability to minimize voltage deviation.

III.4.1 Objective

The goal is to design a FLC that regulates the hydrogen flow rate in an SOFC system. This is achieved by adjusting the hydrogen and oxygen flow rates based on the error and the change in error between the desired and actual output voltages.

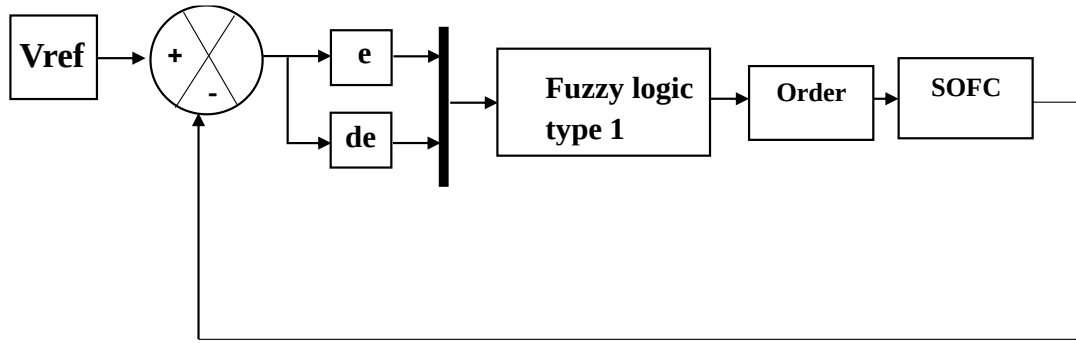


Figure III.3: Control SOFC by fuzzy logic type1

III.4.2 System inputs and output

- **Inputs:**
 - Error (e): The difference between the desired and actual SOFC output voltage.
 - Change in Error (Δe): The rate of change of the error over time.
- **Output:**
 - Control Signal(order): The valve angle controlling the hydrogen and oxygen flow rates.

III.4.3 Fuzzification

Both the error and change in error are fuzzified using membership functions. These functions map the crisp input values to fuzzy sets, allowing the controller to handle uncertainties and nonlinearities inherent in the system[123]. For instance, the error might have membership functions like Negative (N), Zero (Z), and Positive (P), while the change in error could have similar fuzzy sets[124].

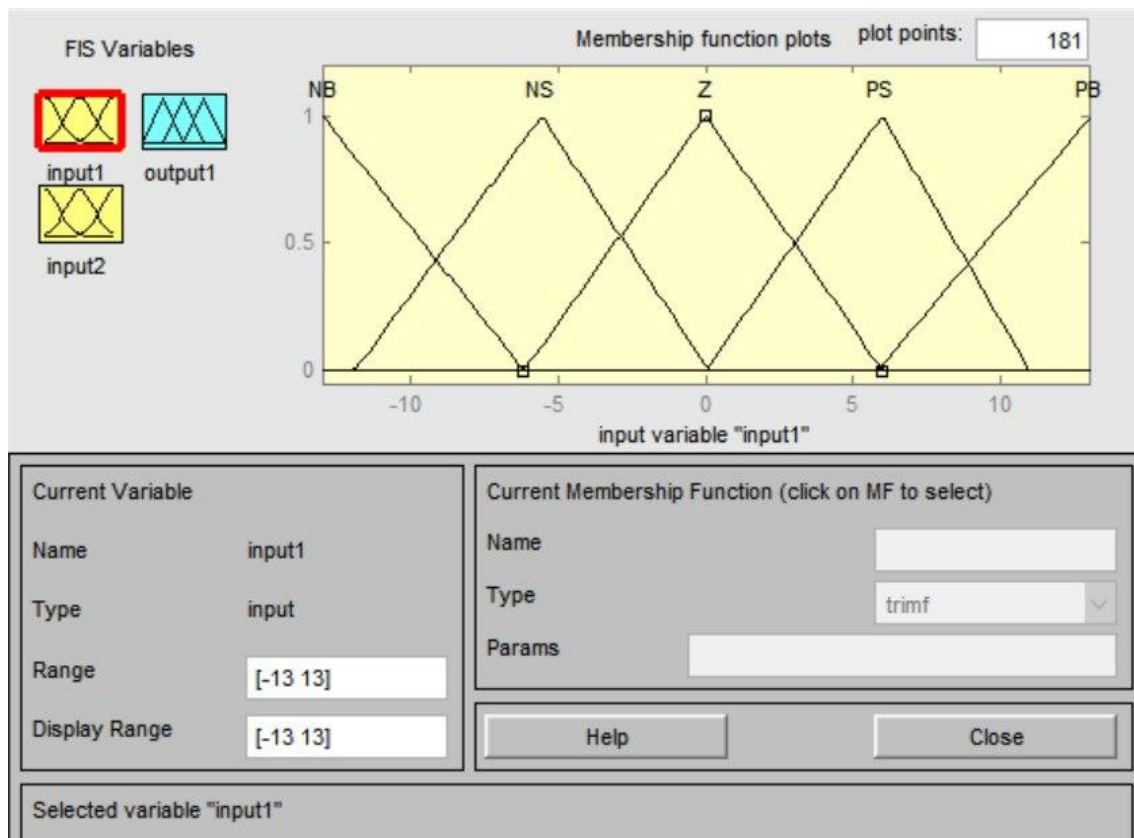


Figure III.4: Input1error

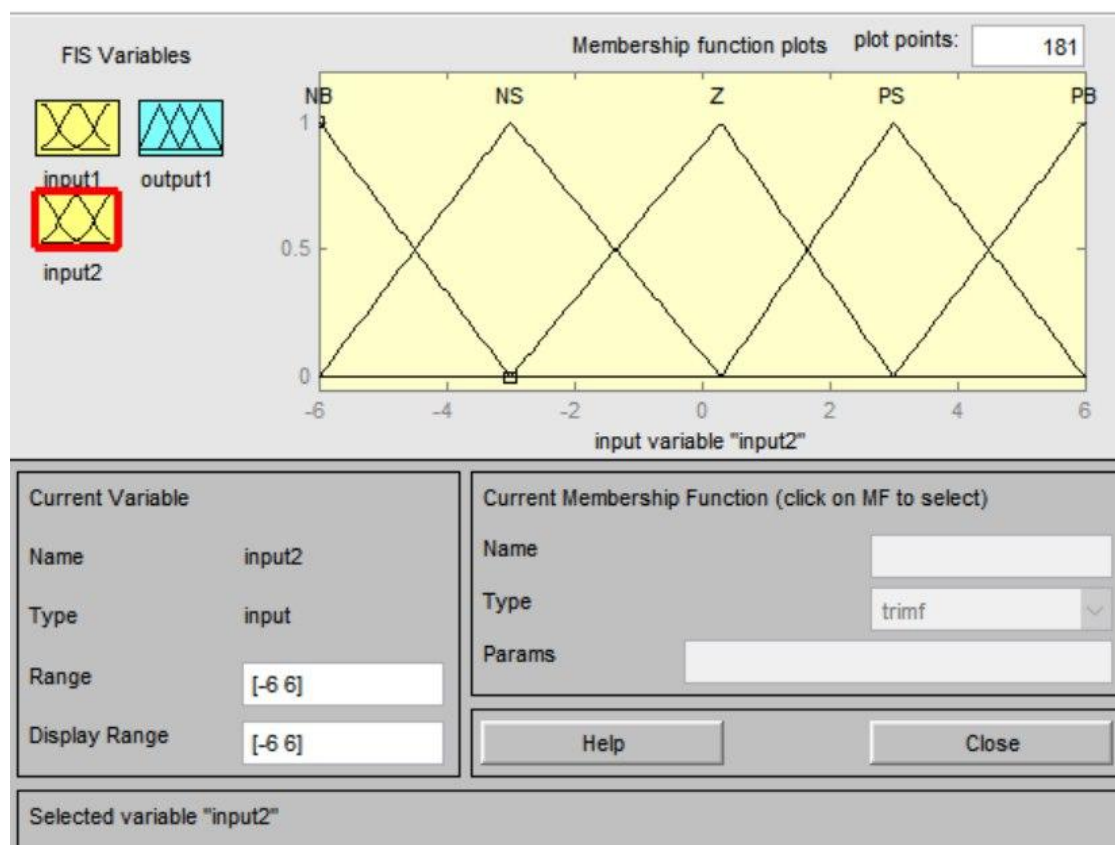


Figure III.5: derivative error

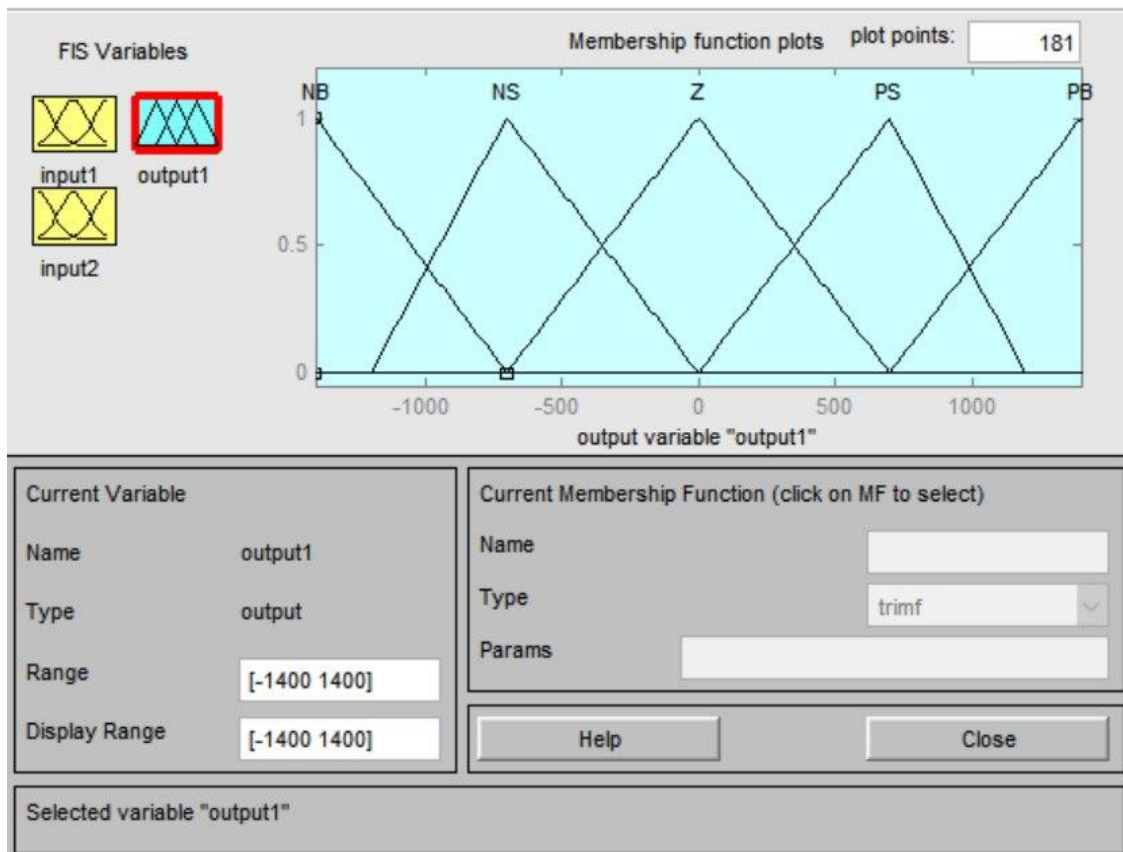


Figure III.6: Output(order)

III.4.4 Rule base

Defuzzification; is the process of converting the fuzzy output-expressed in terms of linguistic variables -into a single crisp numerical value that can be used to control the system. This step is crucial because, while fuzzy logic systems handle uncertainty and imprecision well, controllers typically require exact numerical inputs to perform actions [124].

Change of error signal de(t)	Error signal e(t)				
	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

Table III.1: Fuzzy rules for type1

NB: Negative Big

NS: Negative Small

Z: Zero

PS: Positive Small

PB: Positive Big

III.4.5 Results of simulation

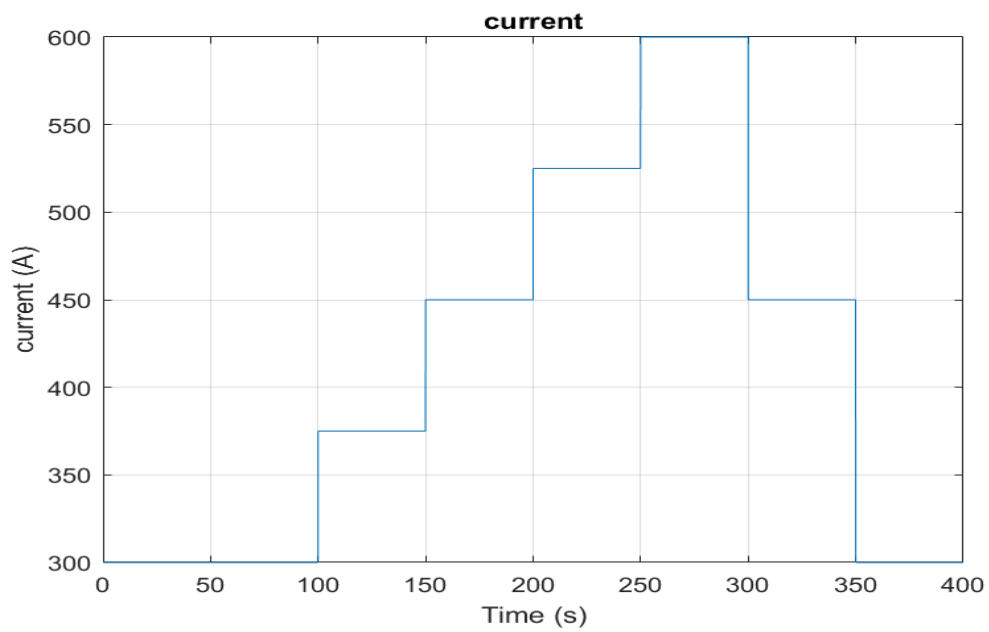


Figure III.7: Current curve

III.4.6 Comparative study

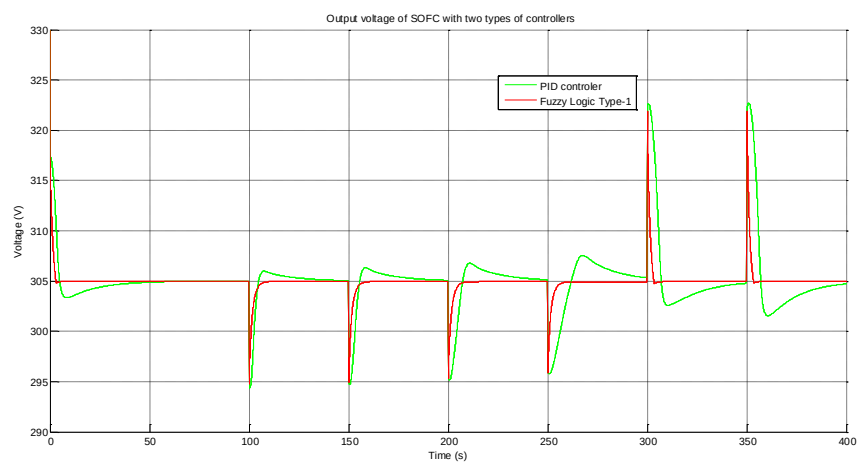


Figure III.8: Comparison of PID and Type-1 Fuzzy Logic Controllers for SOFC Output Voltage Regulation at 305V

III.4.6.1 Qualitative Comparison of SOFC Output Voltage with Two Controllers

The figure of Output voltage of SOFC with two types of controllers:

- * PID Controller with green line
- * Fuzzy Logic Type-1 Controller with red line

Observations:

$t \approx 0-20$ s: The PID controller exhibits an overshoot before settling.

The Fuzzy Logic Type-1 controller settles faster and with less overshoot.

at $t \approx 100$ s, 150 s, 200 s, etc...: The PID controller shows larger voltage dips and takes more time to stabilize after disturbances but the Fuzzy Logic controller consistently shows faster recovery and smaller deviations.

Steady-State Behavior:

The Fuzzy Logic controller maintains a more stable and consistent voltage over time on other hand the PID controller introduces oscillations and slower convergence.

Transient Peaks ($t \approx 300$ s and 350 s): The PID controller exhibits significant voltage spikes, suggesting sensitivity to abrupt change. However the Fuzzy Logic controller handles these events more smoothly.

III.4.6.2 Conclusion:

The Fuzzy Logic Type-1 controller outperforms the PID controller in regulating of the output voltage of the SOFC system.

It offers:

- ✓ Faster settling time
 - ✓ Lower overshoot
 - ✓ Better disturbance rejection
 - ✓ More stable long-term behavior
- This makes the Fuzzy Logic controller a more robust and efficient choice for dynamic SOFC control.

III.5 Fuzzy Type2

Generalized Type-2 Fuzzy Models extend the foundational concepts of Type-1 Fuzzy Models by incorporating Type-2 fuzzy sets, enhancing their ability to handle uncertainty. These models have been proposed as essential components for constructing fuzzy systems, with claims emphasizing their relevance in various applications. One key advantage of fuzzy controllers is their adaptability in response to disturbances within a system [125].

III.5.1 Objective

In particular, Generalized T2-FLC demonstrates improved stability in simulations. When subjected to noise, T2-FLC exhibits superior stability characteristics compared to other approaches, reinforcing its effectiveness in dynamic environments.

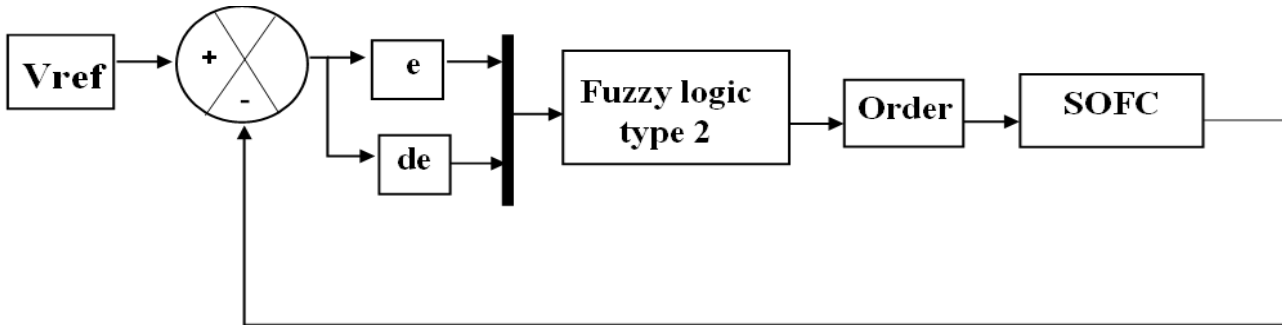


Figure III.9: Control SOFC by fuzzy logic type 2

III.5.2 Fuzzification

In the proposed control framework, the input to the Type-2 Fuzzy Logic Controller is based on the voltage error, defined as the difference between the reference value and the actual measured current. Additionally, the derivative of the error serves as a secondary input, capturing the rate of change in deviation-thereby enhancing the controller's responsiveness to dynamic fluctuations.

The Type-2 fuzzy inference mechanism employs membership functions for both the error and its derivative. These functions are defined over five linguistic labels:

NB (Negative Big), N (Negative), Z(Zero), P (Positive), PB (Positive Big)

All the membership functions are of Gaussian type, chosen for their smoothness and ability to model uncertainty gracefully. This is particularly advantageous in dynamic environments.

The controller's output, visualized in Figures 10, 11, and 12, demonstrates the system's regulated voltage response [126].

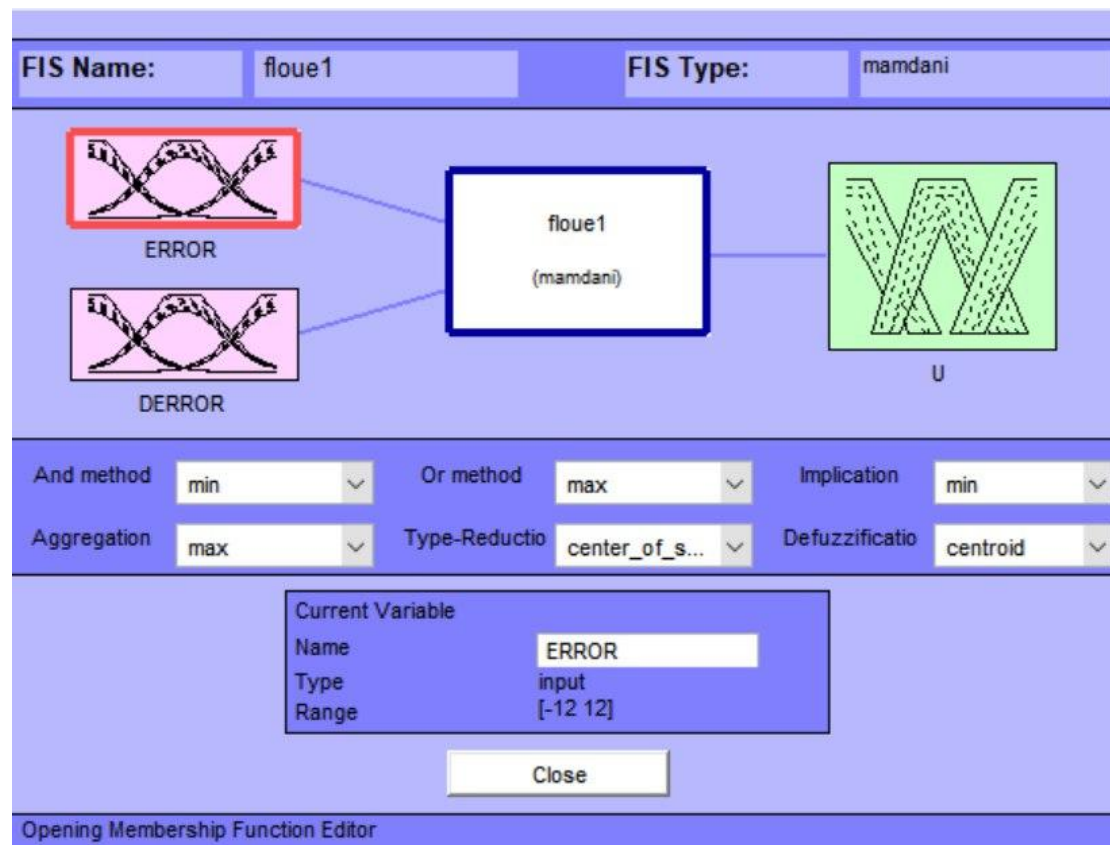


Figure III.10: Membership function of Fuzzy logic control type2

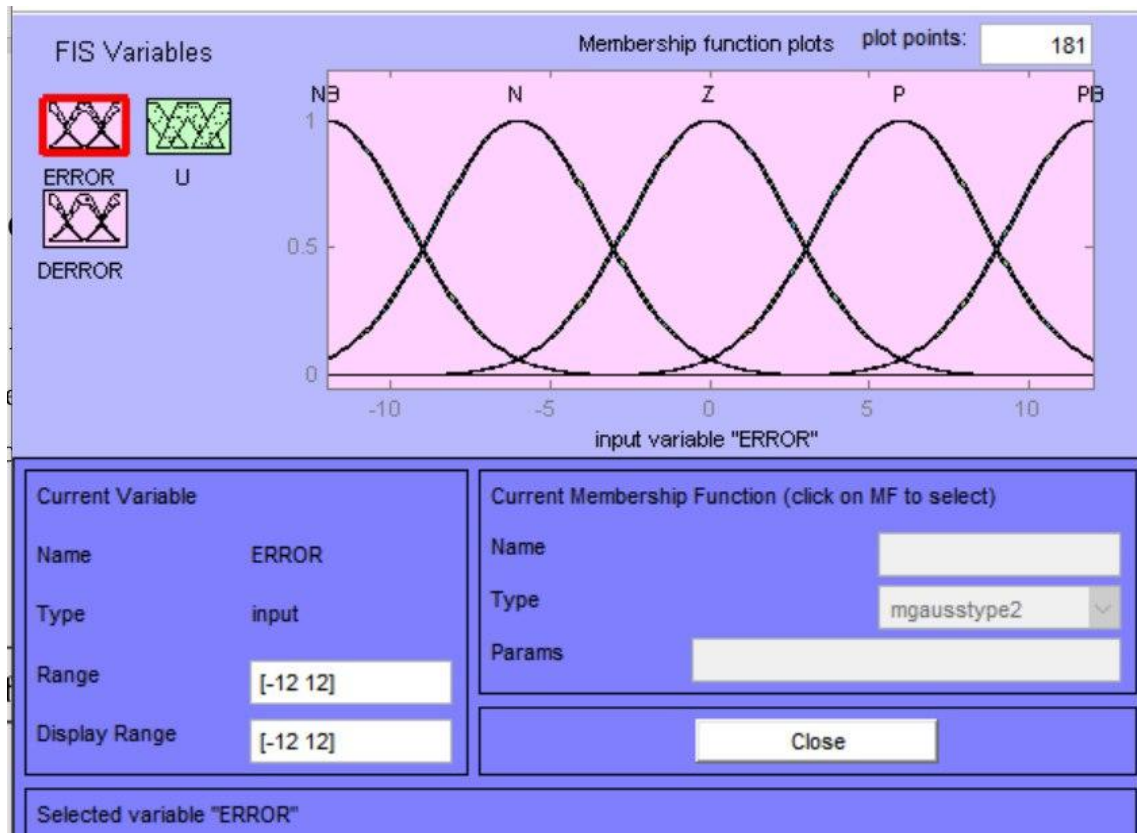


Figure III.11: Input1 (error)

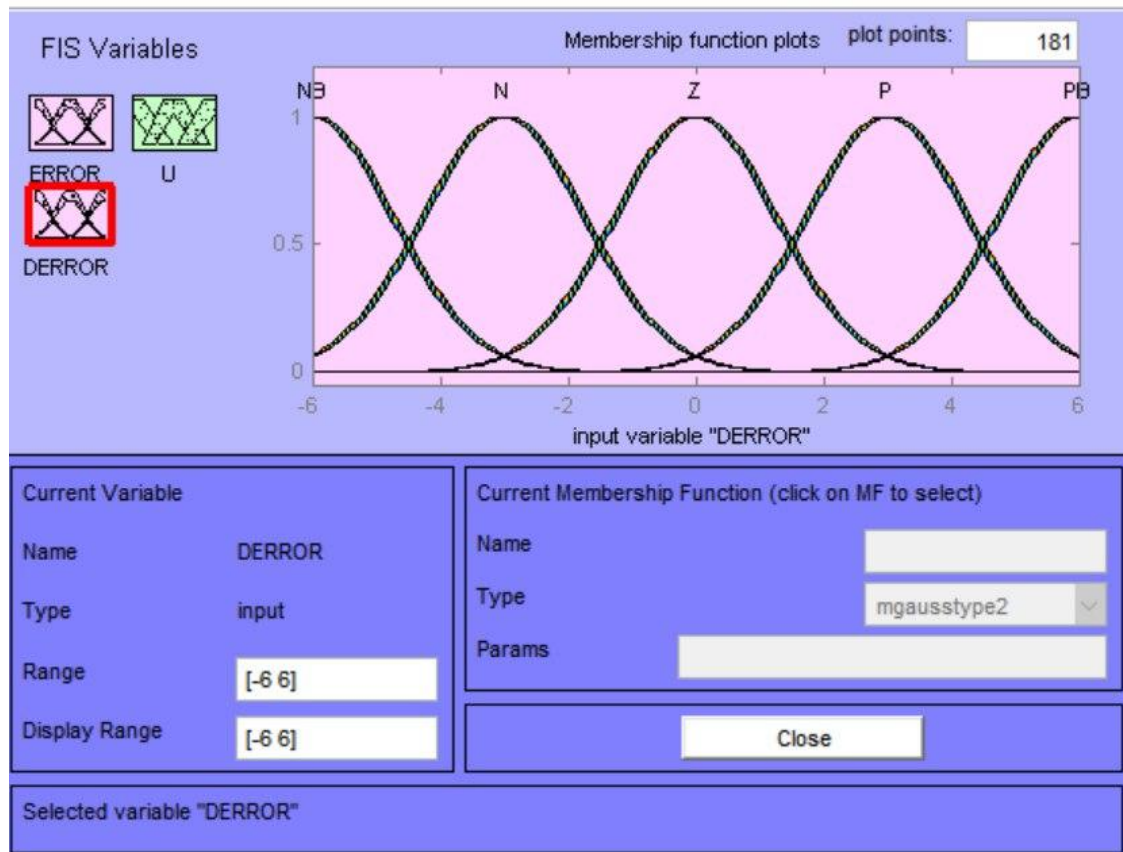


Figure III.12: Input 2(derivative error)

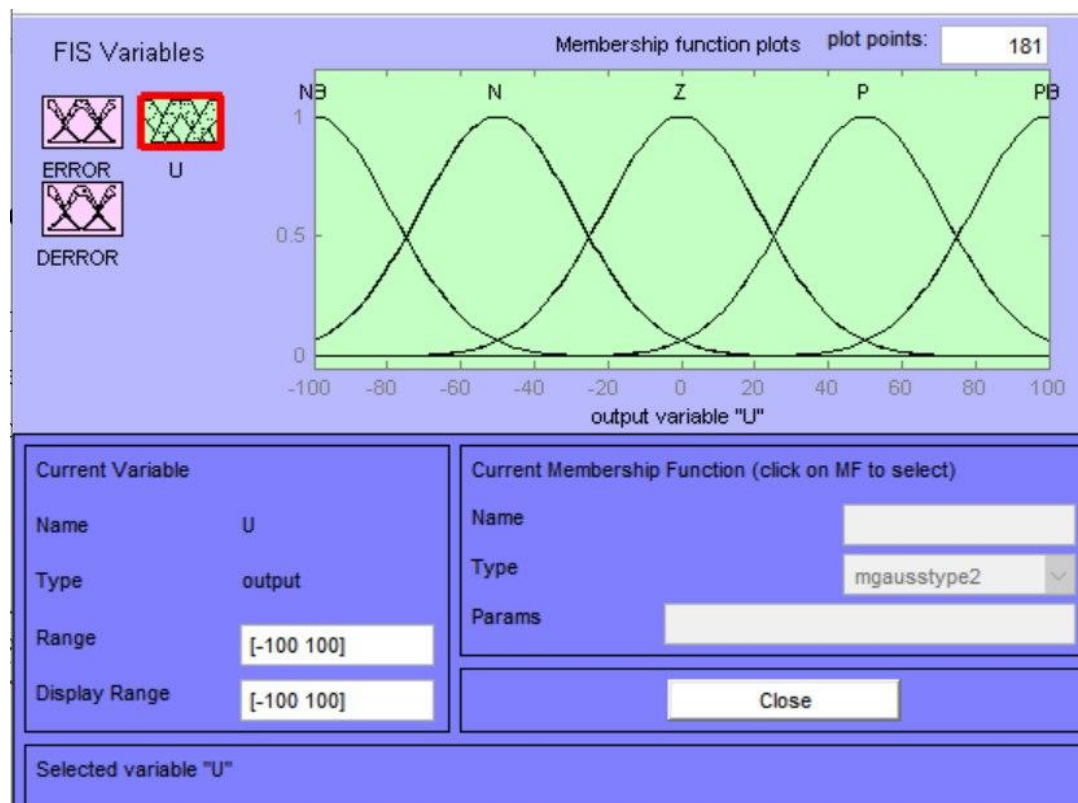


Figure III.13: Output signal of T2-FLC

III.5.2 Rule base

Change of error signal $de(t)$	Error signal $e(t)$				
	NB	NS	Z	PS	PB
NB	NB	NB	N	N	Z
NS	NB	N	N	Z	PS
Z	N	N	Z	PS	PS
PS	N	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

Table III.2: Fuzzy rules of type2

NB: Negative Big

N: Negative

Z: Zero

PS: Positive Small

PB: Positive Big

III.5.3 Simulation results

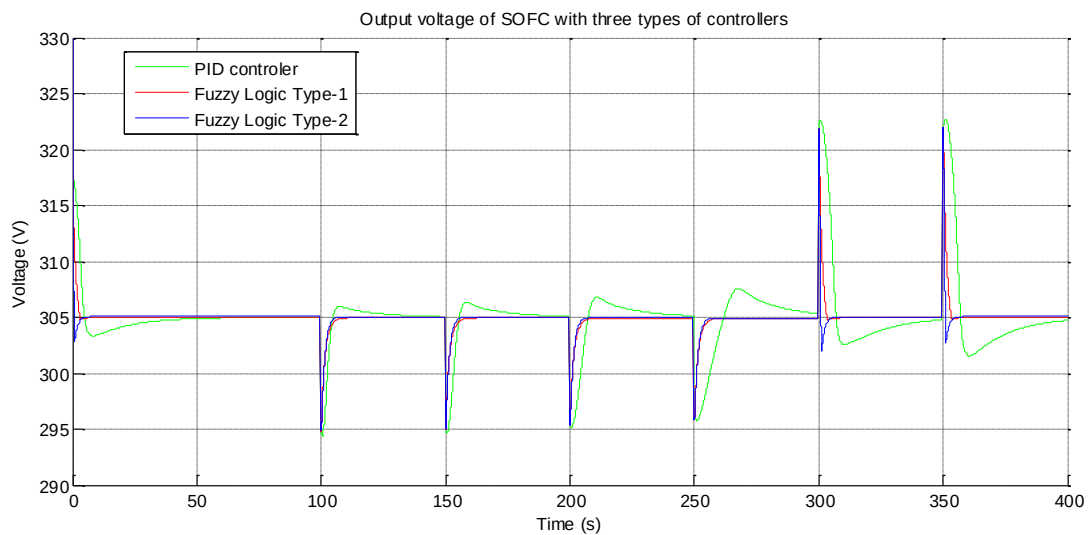


Figure III.14: Control output voltage of SOFC through PID controller, T1-FLC and T2-FLC

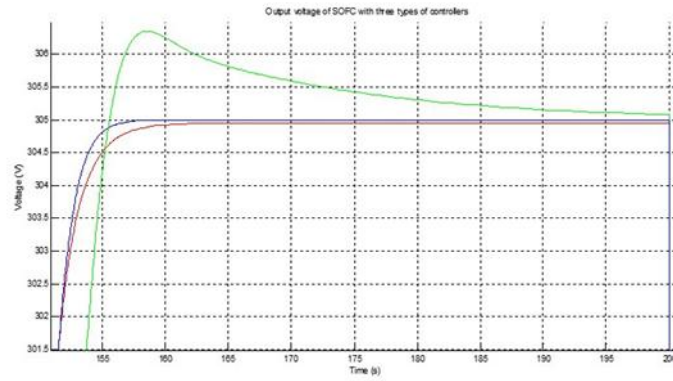


Figure III.15: Zoomed-In dynamic response.

III.5.4 Qualitative Study of Output Voltage of SOFC with Three Types of Controllers

The two graphs represent the dynamic behavior of SOFC output voltage controlled using three different types of controllers:

- * PID Controller with green
- * Fuzzy Logic Type-1 Controller with red
- * Fuzzy Logic Type-2 Controller with blue

➤ Long-Term Response with Disturbances:

The second graph assesses the controllers' performance under multiple disturbances. The PID controller displays significant weaknesses, large amplitude overshoots and undershoots recur at each disturbance (~100s to 350s), and the system shows prolonged recovery times, indicating poor robustness.

The T1-FLC performs more consistently, showing smaller deviations and steadier correction. Yet again, the T2-FLC outshines both, maintaining voltage stability with minimal overshoot, rapid disturbance rejection, and negligible steady-state error.

➤ Zoomed-In Dynamic Response:

The PID controller exhibits a pronounced overshoot, peaking above 308V, followed by oscillatory behavior before stabilizing near 305V. This indicates a lack of precision and responsiveness to abrupt changes.

In contrast, the Type-1 Fuzzy Logic Controller demonstrates superior control with a smoother voltage curve, minimal overshoot, and faster settling at the desired value. However, the Type-2 Fuzzy

Logic Controller further refines this performance its response is not only smoother, but also quicker in achieving steady-state, reflecting enhanced transient management capabilities.

III.5.5 Quantitative comparison

In the second comparison, four performance criteria are used to evaluate the deviation between the actual speed response and the ideal step-type (set-point) response. To quantify this difference, we calculate the integral of a positive error-related function over time.

This error-based index increases in magnitude as the actual response deviates further from the ideal. In practical terms, the integral is evaluated over a time interval $[0, T]$, where T is selected to fully encompass the system's transient behavior. This ensures the index reflects the total discrepancy during the response phase [126]:

Integral Absolute Error:

$$IAE = \int_0^T |e(t)| dt \quad (III.1)$$

Integral Squared Error:

$$ISE = \int_0^T e^2 dt \quad (III.2)$$

Integral of the Time-Weighted Absolute Error:

$$ITAE = \int_0^T t \cdot |e(t)| dt \quad (III.3)$$

Integral of Time multiplied by the Squared Error:

$$ITSE = \int_0^T t \cdot e^2 dt \quad (III.4)$$

Control Index	PID	Fuzzy logic type1	Fuzzy logic type2
IAE	621.772	129.2559	100.2888
ISE	4.3848e+03	736.1723	513.579
ITAE	2.51009e+05	2.681e+04	2.034e+04
ITSE	1.1407e+06	1.6544e+05	1.0937e+05

Table III.3: IAE, ISE, ITAE and ITSE performance indexes.

III.5.6 Comparison of fuel flow

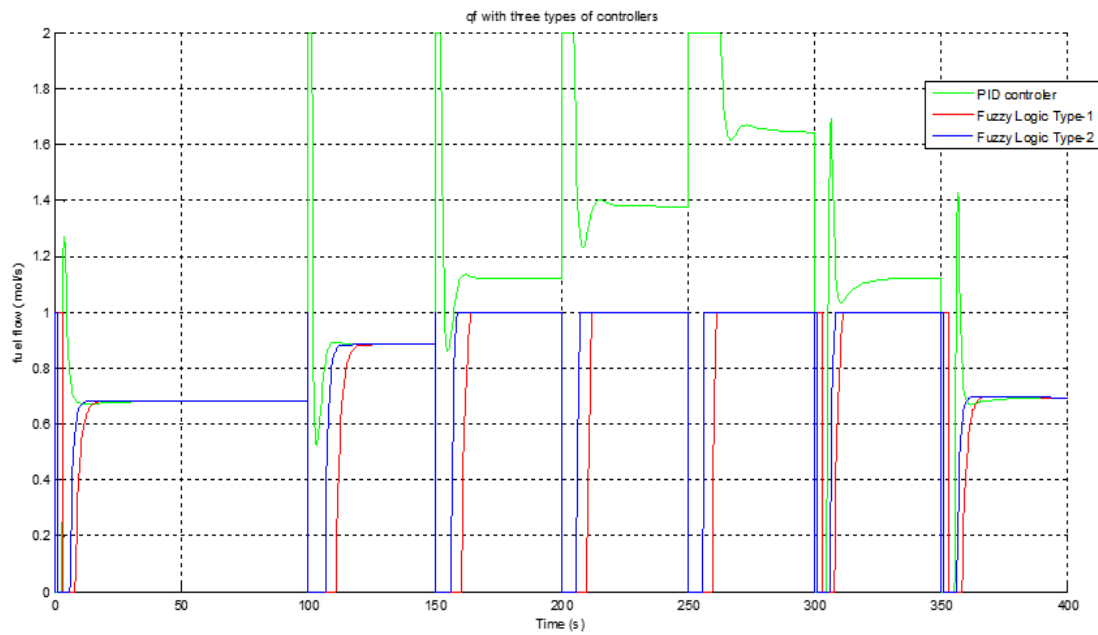


Figure III.16: Comparison response of q_f with PID controller and fuzzy logic type 1 and 2

The comparison

This figure represents the behavior of fuel flow rate q_f , the input hydrogen fuel rate under the control of three strategies:

- PID controller, green
- Fuzzy Logic Type-1, red
- Fuzzy Logic Type-2, blue

Performance Metric	PID Controller	Fuzzy Logic Type-1	Fuzzy Logic Type-2
Rise Time	Fast	Fast	Fast
Settling Time	Moderate	Long (slow settling with oscillations)	Short (quick settling)
Overshoot	Moderate	High	Minimal or None
Steady-State Accuracy	Good	Moderate (slight steady-state error)	Excellent (closely tracks input)
Stability	Stable	Poor (oscillatory and unstable)	Very Stable
Response to Changes	Reasonable	Poor (struggles with changes)	Excellent (smooth transitions)
Robustness	Moderate	Low	High

Table III.4: Comparison of qf with three types of controllers

Conclusion

Fuzzy Logic Type-2 Controller shows superior performance overall in terms of rise time, overshoot, settling time, and steady-state error. It is also more robust and stable, making it the best choice among PID Controller provides decent performance but is not smoothor. Fuzzy LogicType1Controller performs the worst, with significant overshoot and instability, especially during input changes.

III.5.7 Comparison of Utilization

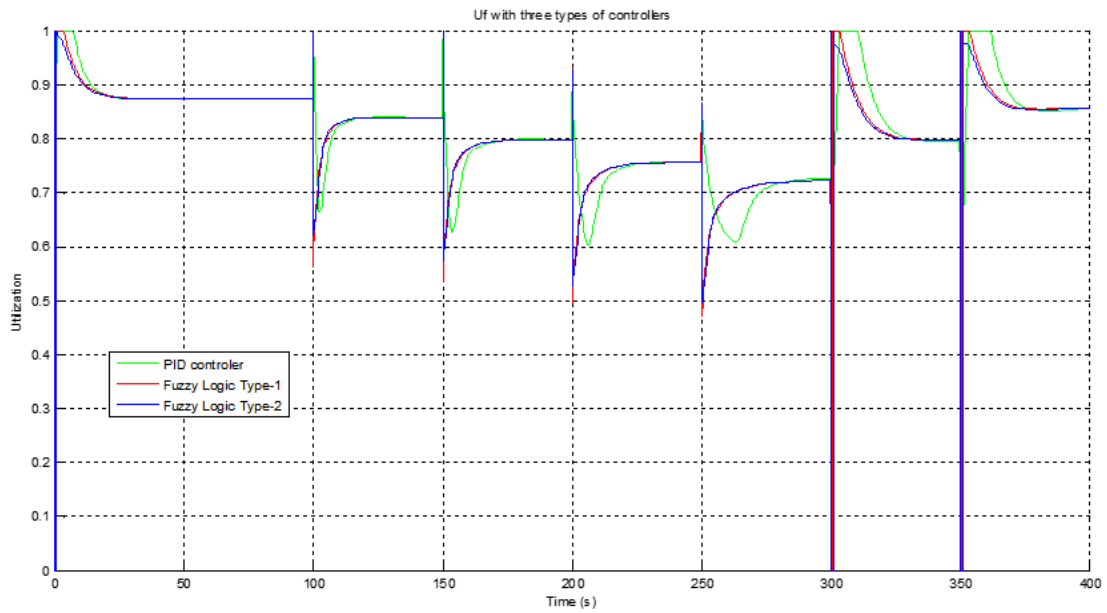


Figure III.17: Utilization (U_f) with PID control, fuzzy logic type1 and type2

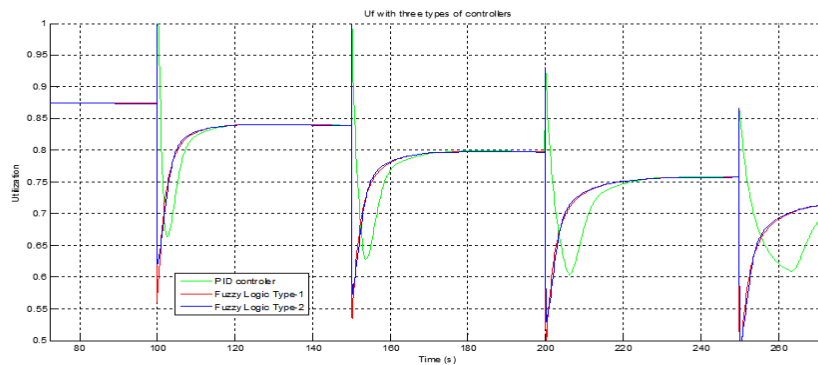


Figure III.18: Zoomed in dynamic response of Utilization (U_f)

III.5.7.1 Comparison of simulation

These figures show the utilization factor U_f of the Solid Oxide Fuel Cell (SOFC) system over time under different control strategies:

- PID controller with green
- Fuzzy Logic Type-1 controller with red
- Fuzzy Logic Type-2 controller with blue

The utilization in SOFCs is typically defined as:

$$U_f = \frac{\text{Hydrogen consumed}}{\text{Hydrogen supplied}}$$

It reflects how effectively the fuel cell uses the input hydrogen to produce electricity.

Aspect	PID Controller	T1-FLC	T2-FLC
Response Time	Fast	Slightly slower	Moderate
Overshoot	High (notable oscillations)	Lower than PID	Minimal
Stability	Less stable (oscillatory)	More stable	Most stable
Smoothness	Less smooth	Smoother	Smoothest
Control Precision	Reactive	Adaptive	Highly adaptive

Table III.5: Comparison curve of Utilization controlled with three types of controllers

III.5.7.2 The results

The PID controller provides a quick response but at the cost of higher oscillations and reduced stability. T1-FLC improves on this with a smoother response and better stability.

However, T2-FLC exhibits the best performance overall-balancing response time, minimizing overshoot, and offering the most stable and precise control.

In contexts where robustness and fine-tuned stability are critical-especially in systems affected by uncertainty or noise T2-FLC would be the preferred choice.

III.5.8 Comparison of oxygen flow

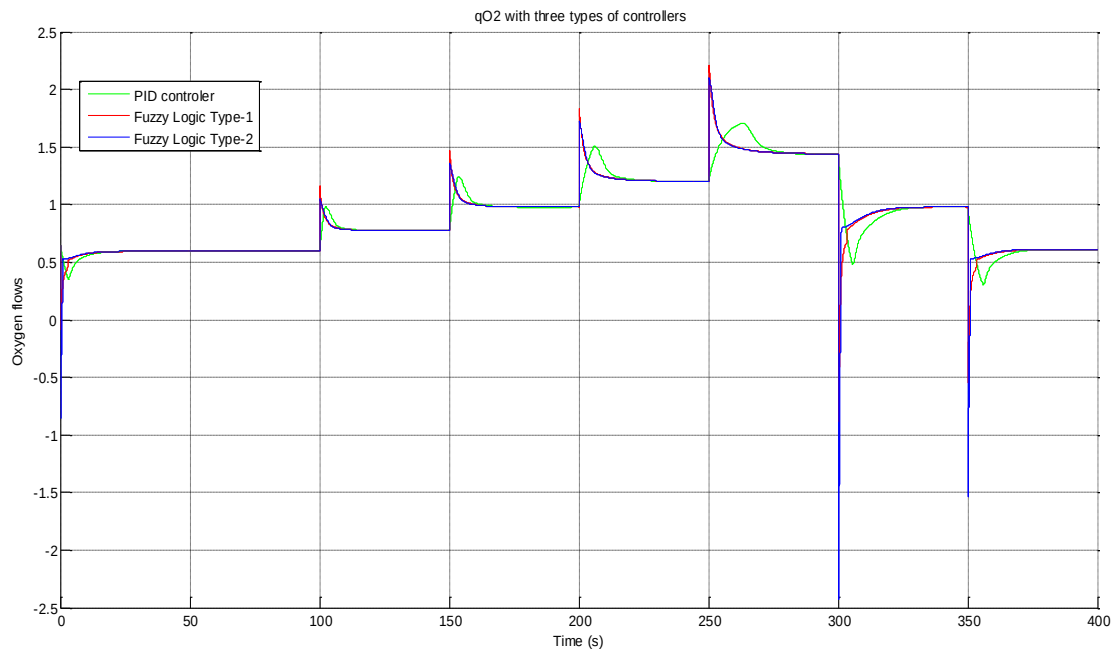


Figure III.19: Oxygen flows qO_2 controlled with PID controller and fuzzy logic type 1 and 2

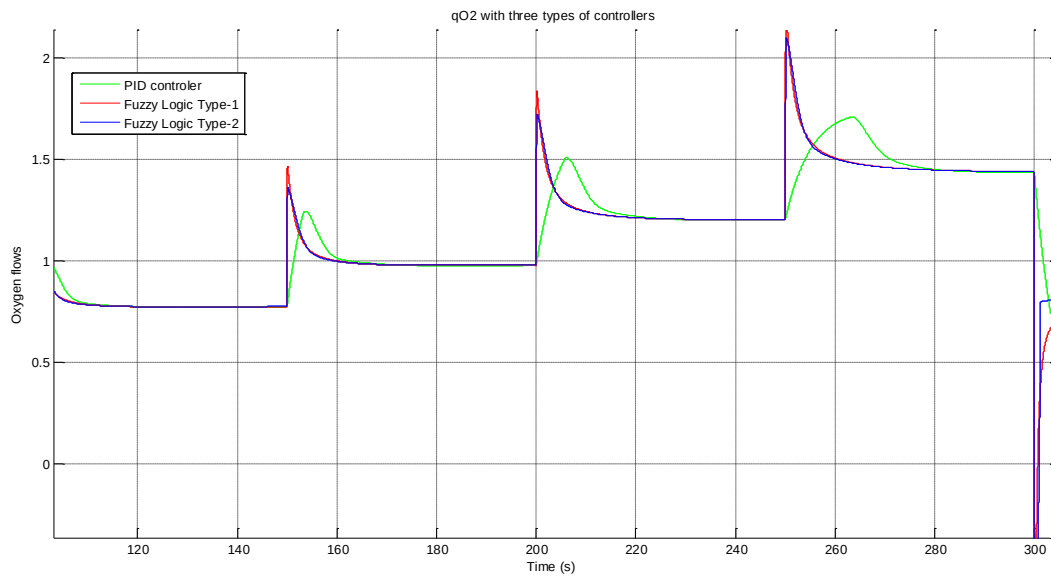


Figure III.20: Zoomed in dynamic response

III.5.8.1 comparison of simulation:

The curve shows the oxygen flow rate qO_2 response under three controllers:

- PID controller with green
- T1-FLC with red
- T2-FLC with blue

Aspect	PID Controller	Type-1 FLC	Type-2 FLC
Response Time	Fast but with spikes	Fast and more controlled	Fast and smooth
Overshoot	Noticeable overshoot at each transition	Moderate overshoot, better than PID	Minimal or none
Settling Time	Long, due to oscillations	Moderate; smoother than PID	Shortest settling time
Stability	Oscillatory behavior after disturbances	Stable with slight ripple	Very stable with fast recovery
Control Smoothness	Irregular and erratic changes	Smoother changes	Smoothest and most consistent
Adaptability	Reacts, but not efficiently	Adapts better, with controlled correction	Highly adaptive to load changes

Table III.6: Comparison curve of oxygen flows qO_2 controlled with three types of controllers

III.5.8.2 The results

The oxygen flow rate response demonstrates that the T2-FLC provides the most stable and efficient control, with minimal overshoot and smooth adaptation to load changes. The T1- FLC improves over PID by reducing oscillations and overshoot, though it still exhibits slight irregularities. The PID controller, while fast, suffers from high overshoot and instability, especially at abrupt load transitions.

III.6 Conclusion

This chapter presented a practical simulation-based comparison of three control strategies PID, Type-1 Fuzzy Logic Controller, and Type-2 Fuzzy Logic Controller applied to the regulation of fuel and oxygen flows in a SOFC system. Using MATLAB/Simulink, each controller was implemented and tested under identical dynamic scenarios, including step load changes and nonlinear disturbances.

The results showed that the PID controller, while fast, suffers from high overshoot, longer settling times, and decreased robustness under disturbances.

The Type-1 FLC improved stability and smoothness, reducing oscillations but still exhibited some sensitivity to system uncertainties. The Type-2 FLC consistently delivered the best overall performance, demonstrating minimal overshoot, shorter settling times, and high robustness, especially in uncertain or fluctuating conditions.

Comparative analysis of output voltage, fuel flow, oxygen flow, and utilization factor curves confirmed the superior adaptability and stability of Type-2 fuzzy control. These findings support the adoption of T2-FLC for high-performance SOFC systems where precision and resilience are critical

General Conclusion

This thesis investigated and compared three control strategies PID, Type-1 Fuzzy Logic, and Type-2 Fuzzy Logic for the regulation of fuel and oxygen flow rates in a Solid Oxide Fuel Cell (SOFC), aiming to ensure stable output voltage and efficient fuel utilization.

Chapter I introduced the theoretical background of hydrogen energy, electrolysis, fuel cells, and the SOFC structure and operation.

Chapter II presented the control approaches, explaining the principles and behavior of PID, Type-1, and Type-2 fuzzy logic controllers.

Chapter III applied these controllers in MATLAB/Simulink, modeling the SOFC system and evaluating control performance based on dynamic response, overshoot, settling time, and energy efficiency.

Simulation results demonstrated that while the PID controller offers fast response, it lacks robustness and induces oscillations under dynamic load conditions. The Type-1 Fuzzy Logic Controller improved the regulation of fuel and oxygen flows by reducing overshoot and enhancing smoothness, but it showed sensitivity to system uncertainties. The Type-2 Fuzzy Logic Controller achieved the best results, ensuring precise and stable control of both fuel and oxygen flows, minimizing error metrics (IAE, ITAE..), and maintaining consistent voltage output even during disturbances.

In conclusion, the Type-2 Fuzzy Logic Controller stands out as the most effective method for managing the nonlinear dynamics of SOFC systems, offering optimal fuel and oxygen regulation, enhanced stability, and superior adaptability making it a strong candidate for integration into advanced, intelligent energy systems.

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