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Thème

DESIGN, MODELING AND SIMULATION OF PEM FEUL CELL EMULATOR

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الملخص:

الهدف من هذا المشروع هو تصميم ونمذجة محاكي خلية الوقود نوع : PEM ، و لإنجاز هذا المشروع اخترنا عنصر تحكم من نوع PI ، محول مستمر-مستمر خافض للتوتر كمصدر للطاقة, يحاكي سلوك هذا النوع من البطاريات.

الكلمات المفتاحية : FC، PEM، المحاكي ، محول مستمر-مستمر خافض للتوتر ، وحدة تحكم PI

Abstract:

The goal of this project is to design, model and simulate an emulator of a PEM fuel cell type, through this project we have chosen a PI control type, a DC-DC buck converter as part of the power in order to emulate the behavior of PEMFC emulator.

Keywords: FC, PEM, emulator, DC-DC buck, PI controller.

Résumé:

Le but de ce projet est de faire la conception, la modélisation et la simulation d'un émulateur d'une pile à combustible de type PEM-FC, à travers de ce projet on a choisir un contrôleur de type PI, un convertisseur DC-DC buck comme partie de puissance afin d'émuler le comportement de cette type de pile.

Mots clés : FC, PEM, émulateur, DC-DC buck, PI contrôleur.

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**GENERAL
INTRODUCTION**

Generale introduction:

Currently, the world is facing major challenges in energy production to fit all the demands around the globe such as in residential, industries and automotive. The demands had to be fulfilled along with minimizing the environmental effects.

Fossil fuels are currently being the dominant sources in most applications with low efficiency, and gives damaging to the environment. Thus, an alternative energy sources and green energy are needed such as wind, solar and fuel cell. Alternative energy sources can contribute to the increasing energy demands of many applications. Recently, fuel cell is famous for its advantages of cleaner, efficiency and silent operation compared to other fossil fuels, Emulation is one strategy in pursuit of digital preservation and combating obsolescence. Emulation focuses on recreating an original computer environment, which can be time-consuming and difficult to achieve, but valuable because of its ability to maintain a closer connection to the authenticity of the digital object, operating system, or even gaming platform. Emulation addresses the original hardware and software environment of the digital object, and recreates it on a current machine.[29] The emulator allows the user to have access to any kind of application or operating system on a current platform, while the software runs as it did in its original environment, Fuel cells run on hydrogen and oxygen to generate electricity. Basically, primary cell or battery is also a device that produces electrochemical energy, but it is cannot beside once the battery is discharged. Similar to the secondary battery which is also having a limited life in generating electricity. However,it is different with fuel cell because fuel cell will continuously produce electricity as long as the fuel and oxidant is supplied There are several types of fuel cell such as Proton Exchange Membrane Fuel Cell (PEMFC), Direct Methanol Fuel Cell (DMFC), Alkaline Fuel Cell (AFC), Solid Oxide Fuel Cell (SOFC), Phosphoric Acid Fuel Cell (PAFC), and Molten Carbonate Fuel Cell (MCFC). PEMFC is the best type of fuel cell because it is having the highest power density compare to other types of fuel cell. However, the cost to implement and create an effective PEMFC is quite expensive . So that, in order to overcome this problem, development of PEMFC emulator using electrical circuit model was designed.

In this project we gone design , modeling and simulation of a PEM-FC emulator For this purpes

This work devided in three main chapter:

- In Chapter one we will find a basics principals of fuel cell its history and its advantage and its applications domain

- Chapter tow we present the modeling step of fuel cell type PEM, the DC-DC buck converter and the synthesis of PI controller
- Chapter three we to simulate the whole of studied system (FC emulator) this simulation made under MATLAB/SIMULINK environment

Finely we terminate this work by general conclusion and perspectives

Chapter I:

Fuel cell system

I.1 introduction:

In this chapter we are going to talk about the fuel cells, its history and its applications, components, overview, how the energy conversion (chemical / electrical) works. Then we focus on the PEM-FC as the studied type.

I.2 developing fuel cell motives:

Amidst projections of fossil fuel shortage within the next century and rising concerns about global warming, there is a growing interest in the development of clean alternative energy. Fuel cells have high power density, fast ignition, a long stack life, and water is the only by-product. Among different types of fuel cells, polymer electrolyte membrane (PEM) fuel cells are favored in automobile applications due to their low operating temperatures and quick responses to load changes [1,2]. Unfortunately, many challenges remain for the wide commercialization of fuel cells. Besides the need to reduce the cost of materials, much remains to be done in terms of understanding the dynamics of fuel cells and optimizing stack design [3]. In addition, stable control of the fuel cell is a difficult problem with inherent tradeoffs and limitations [4].

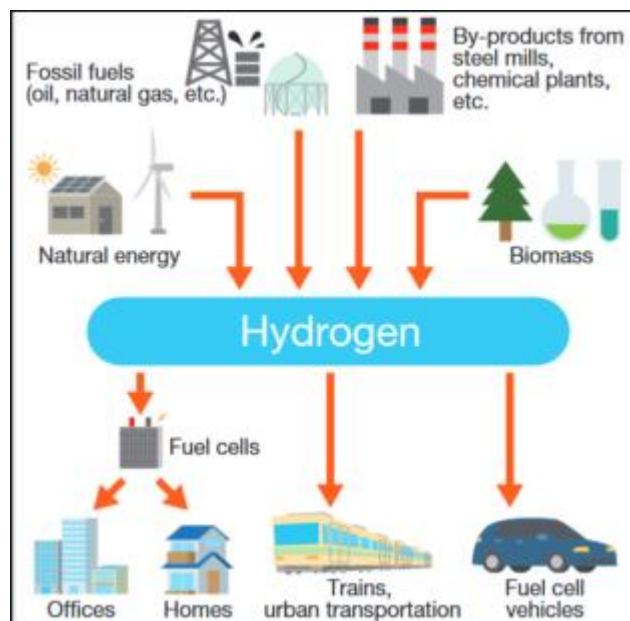


Figure I.1. Hydrogen Society of the Future

I.3 The history of the fuel cell idea:

The first references to hydrogen fuel cells appeared in 1838. In a letter dated October 1838 but published in the December 1838 edition of *The London and Edinburgh Philosophical Magazine and Journal of Science*, Welsh physicist and barrister Sir William Grove wrote about the development of his first crude fuel cells. He used a combination of sheet iron, copper and porcelain plates, and a solution of sulphate of copper and dilute acid. In a letter to the same publication written in December 1838 but published in June 1839, German physicist Christian Friedrich Schönbein discussed the first crude fuel cell that he had invented. His letter discussed

current generated from hydrogen and oxygen dissolved in water. Grove later sketched his design, in 1842, in the same journal. The fuel cell he made used similar materials to today's phosphoric acid fuel cell.

In 1932, Francis Thomas Bacon invented a fuel cell which derived power from hydrogen and oxygen. This was used by NASA to power lights, air-conditioning and communications.

The Brits who bolstered the Moon landings, BBC Archives.

In 1932, English engineer Francis Thomas Bacon successfully developed a 5 kW stationary fuel cell.¹ The alkaline fuel cell (AFC), also known as the Bacon fuel cell after its inventor, is one of the most developed fuel cell technologies, which NASA has used since the mid-1960s.[5,6]

In 1955, W. Thomas Grubb, a chemist working for the General Electric Company (GE), further modified the original fuel cell design by using a sulphonated polystyrene ion-exchange membrane as the electrolyte. Three years later another GE chemist, Leonard Niedrach, devised a way of depositing platinum onto the membrane, which served as catalyst for the necessary hydrogen oxidation and oxygen reduction reactions. This became known as the "Grubb-Niedrach fuel cell". GE went on to develop this technology with NASA and McDonnell Aircraft, leading to its use during Project Gemini. This was the first commercial use of a fuel cell. In 1959, a team led by Harry Ihrig built a 15 kW fuel cell tractor for Allis-Chalmers, which was demonstrated across the U.S. at state fairs. This system used potassium hydroxide as the electrolyte and compressed hydrogen and oxygen as the reactants. Later in 1959, Bacon and his colleagues demonstrated a practical five-kilowatt unit capable of powering a welding machine. In the 1960s, Pratt & Whitney licensed Bacon's U.S. patents for use in the U.S. space program to supply electricity and drinking water (hydrogen and oxygen being readily available from the spacecraft tanks). In 1991, the first hydrogen fuel cell automobile was developed by Roger Billings.[7]

UTC Power was the first company to manufacture and commercialize a large, stationary fuel cell system for use as a co-generation power plant in hospitals, universities and large office buildings

In recognition of the fuel cell industry and America's role in fuel cell development, the US Senate recognized 8 October 2015 as National Hydrogen and Fuel Cell Day, passing S. RES 217. The date was chosen in recognition of the atomic weight of hydrogen (1.008).[8]

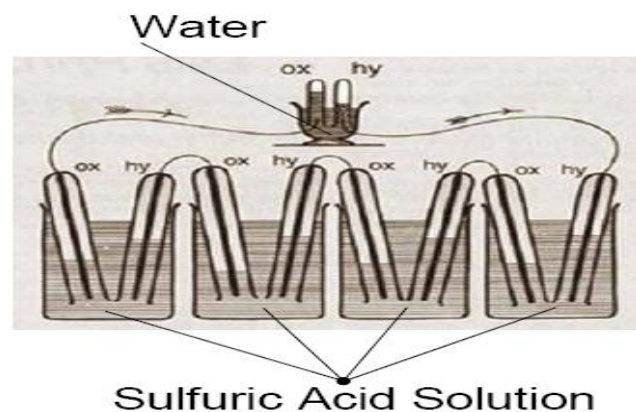


Figure I.2. Sketch of Sir William Grove's 1839 fuel cell

I.4 Fuel Cell : (definition)

Fuel cells are energy conversion devices that produce electricity, electrochemically, from a catalytic aided reaction of a fuel with an oxidant, see Figure (I.3). Molecular hydrogen is the most commonly used fuel, but other hydrogen containing fuels can be used also, depending on the fuel cell type, Oxygen is the most frequently used oxidant for fuel cells and this can be simply obtained from ordinary air, for most fuel cell applications.[9]

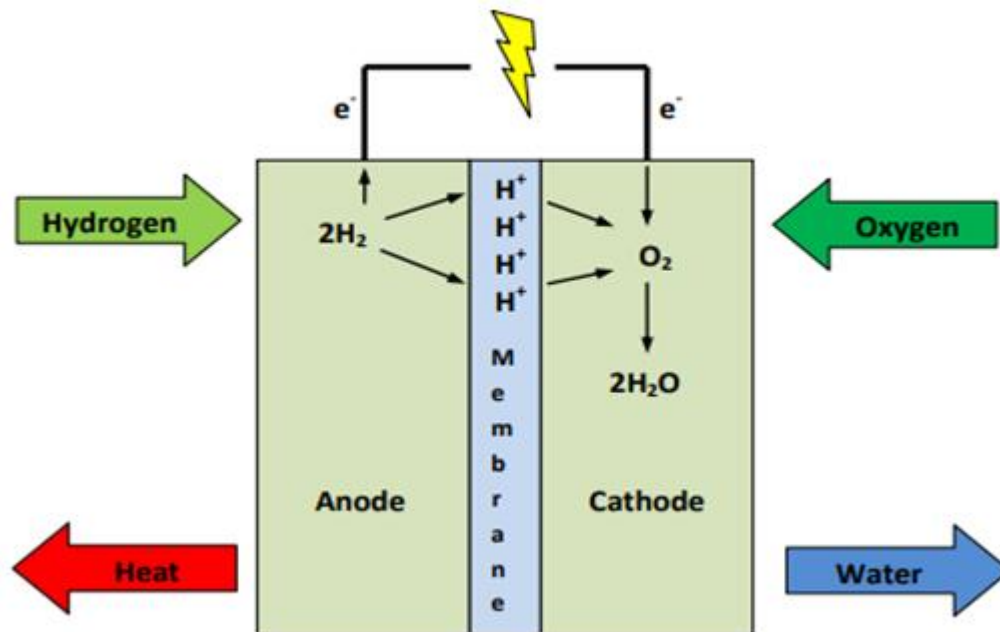


Figure I.3.Schematic of fuel cell

Fuel cells have advantages over heat engines and batteries. Most conventional power generation methods use intermediate steps of producing heat and mechanical work to generate electricity; these steps are avoided with fuel cells, for example fuel cells are not limited by thermodynamic limitations of heat engines, such as the Carnot efficiency and can be switched on and off relatively fast compared to large thermal power stations. Unlike batteries, fuel cells do not suffer cyclic charge/discharge deterioration and if continuously supplied with a fuel, the electrical power of a fuel cell can be sustained indefinitely. Fuel cells offer a promising alternative to traditional power sources; achieving power generation with high efficiency and low environmental impact. Fuel cells have the advantage of being clean, only producing water and heat as by products.

The efficiency of a fuel cell can be quite high but varies depending on the type and system application. In addition, fuel cells have high power density, have no moving parts, have proven durability and robustness, operate silently and can be designed into many shapes and are modular, to obtain the desired amount of electrical power, individual fuel cells are combined to form a fuel cell stack.[10]

I.4.1 Fuel Utilization and Distribution:

PEM fuel cells use hydrogen as the fuel and oxygen as the oxidant and generate electric power via an electrochemical reaction. 80% of the hydrogen used nowadays comes from steam reforming, which is a process that produces greenhouse gases. Despite the fact that hydrogen production is still inefficient and expensive, most fuel cells are operated under excess hydrogen feed. In fact, most literature, including Pukrushpan et al. , Suh and Steganopoulou , and Sun and Kolmanovsky claimed that excess hydrogen and oxygen feed is necessary to avoid operational problems such as stagnant vapor and catalyst degradation. Commercial fuel cells also operate with high stoichiometric hydrogen and air in order to remove the water generated by the redox reaction. So maximum fuel efficiency achieved is only about 50%. Surprisingly, few publications have documented the effects of reactant starvation (i.e. 100% utilization of fuel).

Natarajan and Nguyen examined the effect of varying hydrogen and oxygen flow rates in a single gas channel PEM fuel cell and found that flooding in downstream segments occurred when humidified feeds were used whereas membrane dehydration in upstream segments became a problem when dry feeds were used. Moreover, when hydrogen was starved, downstream segments suffered significant losses in performance. Scholta et al.

Observed similar difficulties in maintaining long-term stability of fuel cell stacks due to non-uniform distribution of gases and inhomogeneous cell humidification. With non-uniform distribution, a single starved cell will essentially limit the overall performance of the stack. Thus, Water uniform reactant distribution is important in flow field design. [10]

I.4.2 Water Management:

The proton conductivity of the membrane in fuel cells depends heavily on water activity. In order to prevent membrane hydration, fuel cells are typically operated with humidified feeds .

At the same time, a lot of effort is put into getting rid of the water generated to prevent flooding in flow channels and gas diffusion layers. Nguyen and Knobbe developed a method of sequentially exhausting each cell in the stack so that water was drained from each cell periodically, which also ensured that gas would flow through each cell. Although this method improved performance, it led to a larger and more complex system since it required individual outlets from each cell in the stack and additional electromechanical control devices, high stoichiometric gas flow rates are often used to drag out liquid water that is accumulated in the serpentine flow channels that is common 2 in commercial fuel cells .

Moreover, the larger the stack, i.e. with more cells connected in series, a larger stoichiometric ratio is required .

However, it is counterintuitive to bring more water into the system by humidifying the reactants when the fuel cell already has difficulty disposing of the water generated by the reaction. A few different approaches have been attempted to eliminate the need to humidify feeds. Watanabe et al. dispersed catalysts into the membrane to create reaction sites inside the membrane to keep it hydrated. Ge et al. used water-absorbing wicks to keep the anode humidified. These authors either modified the MEA or increased the complexity of the fuel cell in order to solve the

paradox of bringing in water while preventing flooding in the system. There should be a way to use the water generated by the reaction to hydrate the MEA enough so that external humidification of feeds is no longer necessary.

This will create an auto-humidified system. The advantage of this is not only to simplify the system by getting rid of the humidifying step but also to increase the reactant utilization ratio.

With dry feeds, lower flow rates can be employed, which allows for higher reactant utilization and thus a more efficient system. For example, Buchi and Srivinisani attempted to operate fuel cells without any external humidification or modifications to conventional membranes. Back-diffusion of water from cathode prevented the anode from drying out and enabled stable long-term operation, but performance was 20-40% lower than that with fully humidified feeds.

Qi and Kaufman used a double-path-type flow-field design that also allowed internal hydration of reactants and membrane for stable long-term operation with dry feeds with only a slight reduction in performance. Benziger et al. developed a stirred tank reactor PEM fuel cell that could also operate with dry feeds.

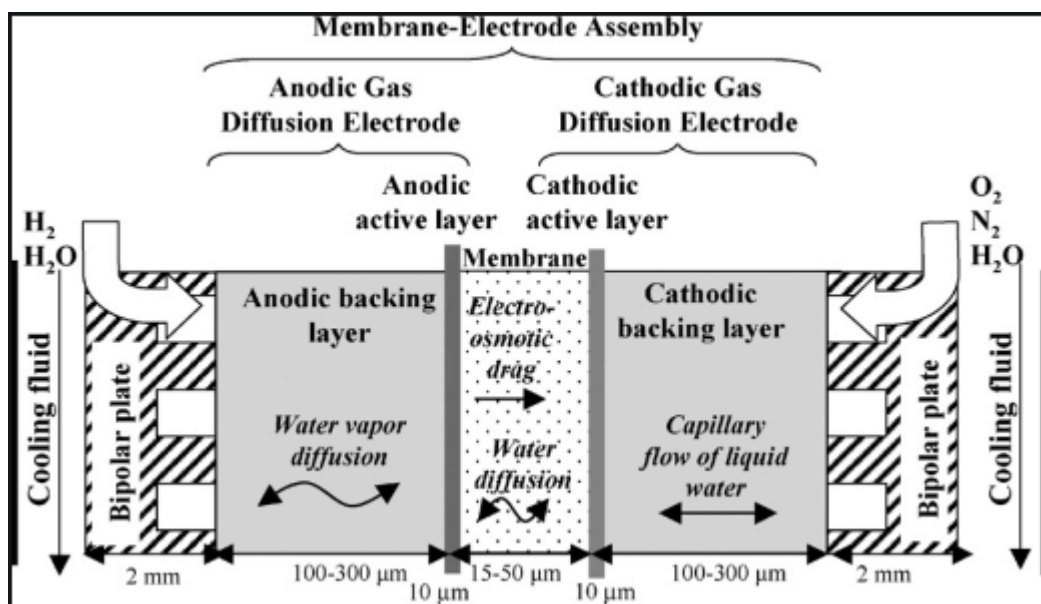


Figure I.4. Water transport mechanisms in fuel cell MEA Active methods for water management

I.4.3 Fuel Cell Type:

A variety of fuel cells are in different stages of development. The most common classification of fuel cells is by the type of electrolyte used in the cells and includes 1) polymer electrolyte fuel cell (PEFC), 2) alkaline fuel cell (AFC), 3) phosphoric acid fuel cell (PAFC), 4) molten carbonate fuel cell (MCFC), and 5) solid oxide fuel cell (SOFC). Broadly, the choice of electrolyte dictates the operating temperature range of the fuel cell. The operating temperature and useful life of a fuel cell dictate the physicochemical and thermomechanical properties of materials used in the cell components (i.e., electrodes, electrolyte, interconnect, current collector, etc.). Aqueous electrolytes are limited to temperatures of about 200 °C or lower because of their high vapor pressure and rapid degradation at higher temperatures. The operating temperature also plays an important role in dictating the degree of fuel processing required. In low-

temperature fuel cells, all the fuel must be converted to hydrogen prior to entering the fuel cell. In addition, the anode catalyst in lowtemperature fuel cells (mainly platinum) is strongly poisoned by CO. In high-temperature fuel cells, CO and even CH₄ can be internally converted to hydrogen or even directly oxidized electrochemically. Table I-1 provides an overview of the key characteristics of the main fuel cell types.

Electrolyte material	Operating temperature	Anticipated applications	Comments
PEMFC	80 °C	Stationary and automobile	Minimum contamination and material problem
AFC	Approx 100 °C	Space program	Susceptible to contamination, very expensive
PAFC	Approx 100 °C	Stationary	Higher temperature and longer warm up time makes unsuitable for vehicles
SOFC	1000 °C	Stationary	Very high temperature create material problems, steam generation could increase efficiency by cogeneration
MCFC	600 °C	Stationary	Same as SOFC

Table I.1. Summary of typical fuel cell characteristics

Fuel cells bear significant resemblance to electrolyzers and electrolytic capacitors. All three devices have similar components; a central electrolyte, which carries ions or electrons from one electrode to the other; two electrodes, one each side of the electrolyte, one positive (cathode) and one negative (anode), where the electrochemical reactions occur; and a catalyst (fuel cell and electrolyser), which speeds the reactions at the electrodes.

Various types of fuel cells have been developed depending on their electrolyte type, ion flow or temperature range,.

This thesis focuses on low temperature fuel cells, particularly the Proton Exchange Membrane (PEM) fuel cell. These fuel cells are in a transition between development and early commercialisation, because of their suitability to mobile and transport applications, which allows a healthy environment for researchers to solve important, fundamental problems.

PEM cells also require less complicated Balance of Plant (BOP) or expensive laboratory facilities to begin research. Many issues with PEM fuel cells are related to material cost and manufacturability of components which can be solved given enough support and focused

research. The PEM fuel cell will be introduced in the next section and a full description of PEM fuel cell technology .

for further information about all other types of fuel cells; their technology, their application and current research

I.5 Proton-exchange membrane fuel cell:

Proton-exchange membrane fuel cells (PEMFC), also known as polymer electrolyte membrane (PEM) fuel cells, are a type of fuel cell being developed mainly for transport applications, as well as for stationary fuel-cell applications and portable fuel-cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special proton-conducting polymer electrolyte membrane. PEMFCs generate electricity and operate on the opposite principle to PEM electrolysis, which consumes electricity. They are a leading candidate to replace the aging alkaline fuel-cell technology, which was used in the Space Shuttle. [12]

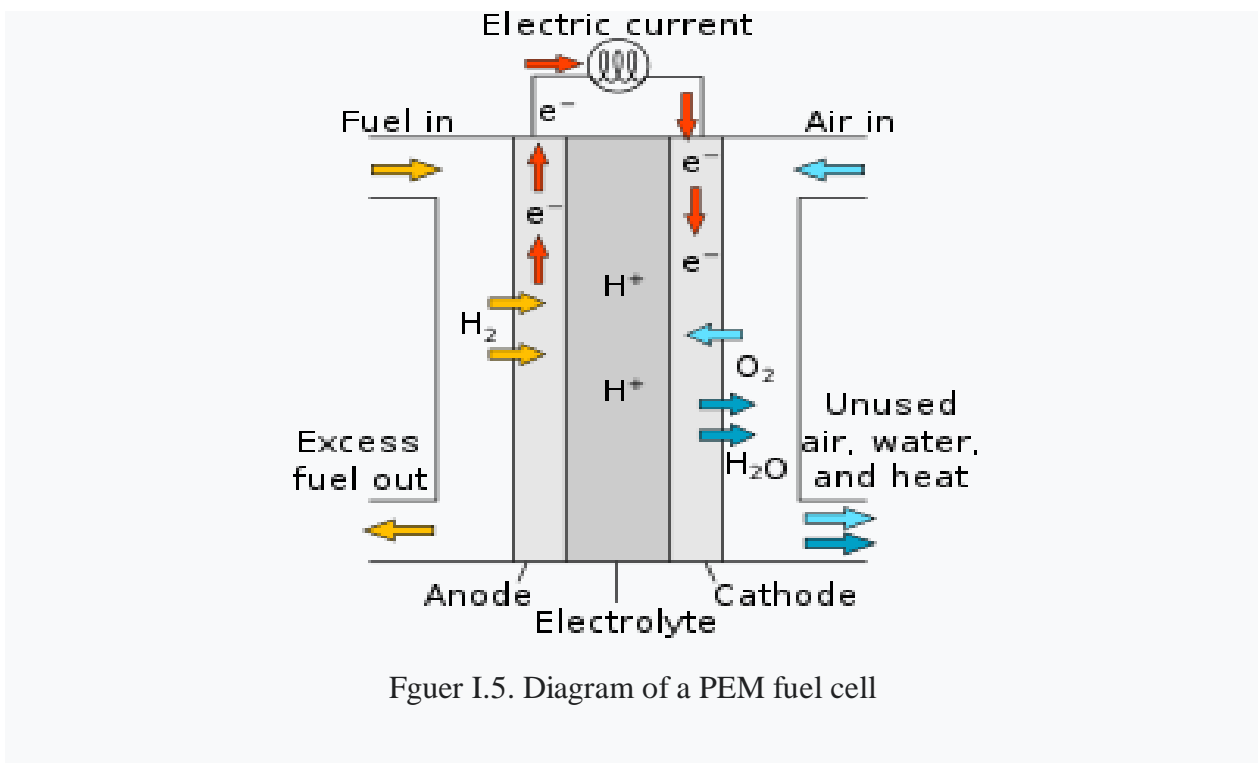


Figure I.5. Diagram of a PEM fuel cell

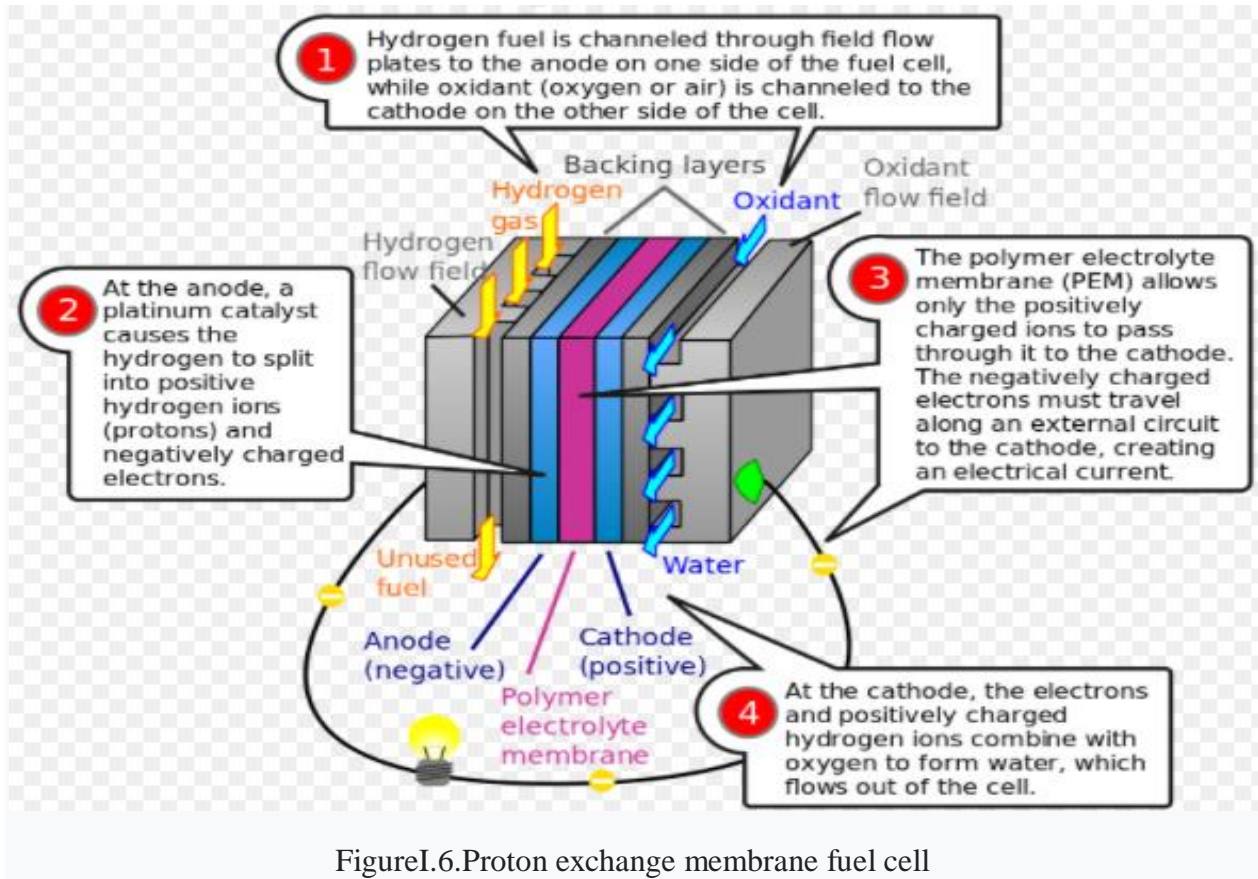


Figure I.6. Proton exchange membrane fuel cell

I.5.1 Science:

PEMFCs are built out of membrane electrode assemblies (MEA) which include the electrodes, electrolyte, catalyst, and gas diffusion layers. An ink of catalyst, carbon, and electrode are sprayed or painted onto the solid electrolyte and carbon paper is hot pressed on either side to protect the inside of the cell and also act as electrodes. The pivotal part of the cell is the triple phase boundary (TPB) where the electrolyte, catalyst, and reactants mix and thus where the cell reactions actually occur. Importantly, the membrane must not be electrically conductive so the half reactions do not mix. Operating temperatures above 100 °C are desired¹ so the water byproduct becomes steam and water management becomes less critical in cell design. [13]

I.5.2 Proton Exchange Membrane Fuel Cell Overview :

Proton Exchange Membrane (PEM) fuel cells are low temperature fuel cells that get their name from the unique electrolyte it uses, a solid phase proton conducting membrane about 0.020mm thick. These fuel cells are almost universally of the planar bipolar type and operate effectively between 60°C - 80°C.

I.5.3 PEM Fuel Cell Components:

Two major components make up the essence of a PEM fuel cell, a Membrane Electrode Assembly (MEA) and flow plates. A MEA which consists of a proton exchange membrane, an electrically conductive porous gas diffusion backing layer and an electro-catalyst at the interface

between the backing layer and the membrane is the heart of the PEM fuel cell and is responsible for the electrochemical reaction. The flow plates distribute the fuel and oxidant to the reactive sites of the MEA via flow channels (flow fields) and electrically connect the cells. Supplementary components of a PEM fuel cell include gaskets, gas connectors, current collectors and backing plates. These additional components are not of major importance in PEM fuel cell research because of the low operating temperature sealing, corrosion, shielding or leaking concerns are minor.[15]

I.5.4 Proton exchange membrane:

The most common material used for the membrane of a PEM fuel cell is Nafion. It was developed by Dr. Walther Grot at DuPont by modifying Teflon. Nafion was the first synthetic polymer ever developed with ionic properties, and it started an entirely new class of polymers called Ionomers . The membrane is located between the cathode and anode layers which allow the flow of hydrogen ions and stops electrons. Electrons then must flow through an external circuit producing electricity. [14]

I.5.5 Catalyst layer:

Due to the low operational temperature of these fuel cells (far below the ignition temperature of hydrogen in air) a very effective catalyst electrode has to be incorporated to ensure the electrochemical reaction takes place. Platinum or platinum alloys are most frequently used . [14]

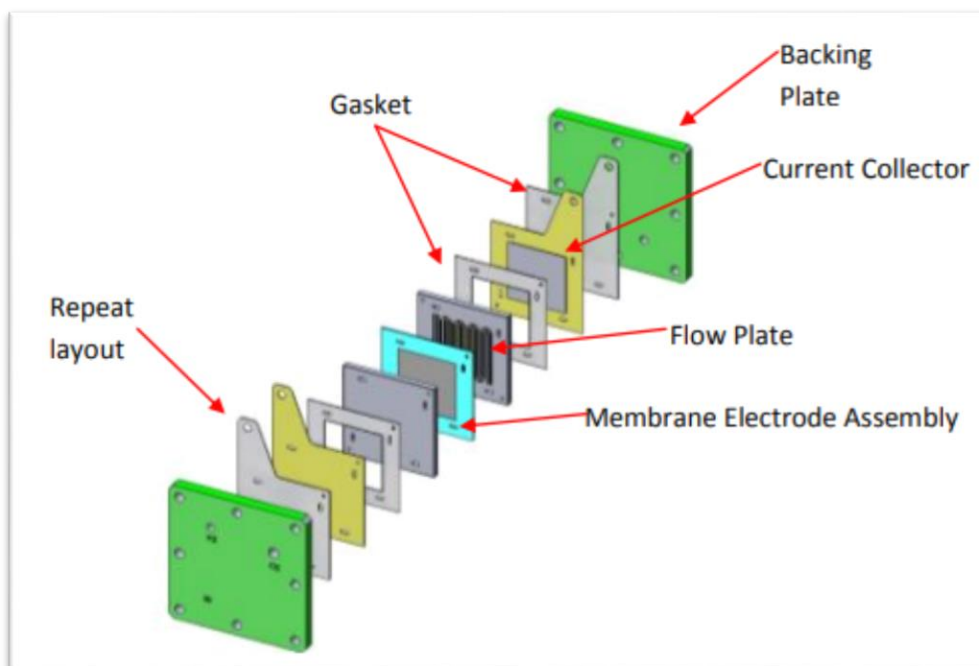


Figure I.7. exploded view of a PEM fuel cell

I.5.6 Gas diffusion layer: exploded view of a pem fuel cell:

The Gas Diffusion Layer (GDL) is a conductive carbon fibre cloth or paper which aids the dispersion of the gases from the flow plates to the catalyst. It is manufactured from carbon cloth or paper material that has been processed through a heat treatment process to toughen it and aid its conductivity . [14]

I.5.7 Flow plates and flow fields:

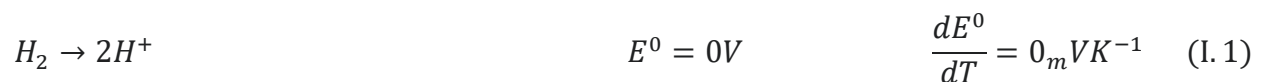
The gas flow plate has many different descriptive names; interconnect; bipolar plate; flow plate; electrode; with respect to the type and the design of the PEM fuel cell. The flow plate is a vital component of a PEM fuel cell, it distributes fuel and oxidant to reactive sites, collects produced current, removes reaction products, manages water through the cell and provides mechanical support for the cells in a stack. Specially designed flow plates, with intricate flow fields imbedded, have to meet the conflicting requirements, of providing good electrical contact and allowing easy passage of the gases concerned, distribute hydrogen to the surface of the anode and air to the surface of the cathode . The flow plate design is very important and it is the main theme of this thesis. The interaction of this component with other components of the PEM fuel cell and the scope of this thesis with relation to the flow plate design . [14]

I.6 Reactions:

A proton exchange membrane fuel cell transforms the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen to electrical energy, as opposed to the direct combustion of hydrogen and oxygen gases to produce thermal energy.

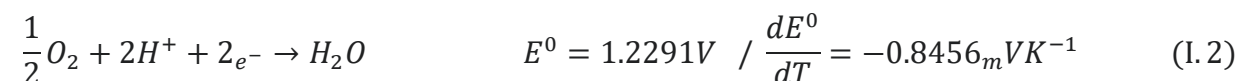
A stream of hydrogen is delivered to the anode side of the MEA. At the anode side it is catalytically split into protons and electrons. This oxidation half-cell reaction or hydrogen oxidation reaction (HOR) is represented by:

At the anode:



The newly formed protons permeate through the polymer electrolyte membrane to the cathode side. The electrons travel along an external load circuit to the cathode side of the MEA, thus creating the current output of the fuel cell. Meanwhile, a stream of oxygen is delivered to the cathode side of the MEA. At the cathode side oxygen molecules react with the protons permeating through the polymer electrolyte membrane and the electrons arriving through the external circuit to form water molecules. This reduction half-cell reaction or oxygen reduction reaction (ORR) is represented by:

At the cathode:



Overall reaction:



The reversible reaction is expressed in the equation and shows the reincorporation of the hydrogen protons and electrons together with the oxygen molecule and the formation of one water molecule. The potentials in each case are given with respect to the standard hydrogen electrode.[14]

I.6.1 The mathematical relation to conversion the energy (chemical/electric):

Energy and the electromotive force (EMF) of the Hydrogen Fuel Cell:

In some electrical power-generating devices, it is very clear what form of energy is being converted into electricity.

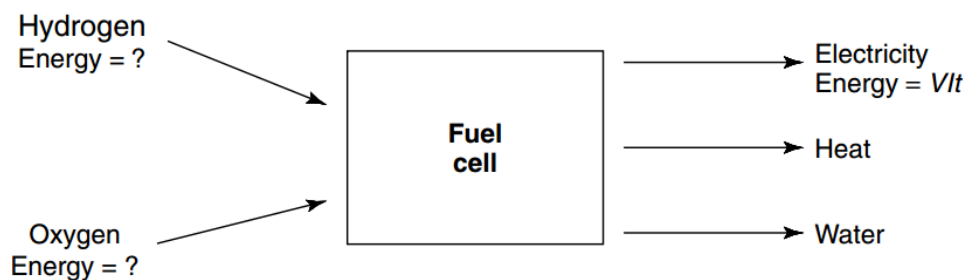


Figure I.8. Fuel cell inputs and outputs.

With a fuel cell, such energy considerations are much more difficult to visualise. The basic operation has already been explained, and the input and outputs are shown in Figure .The electrical power and energy output are easily calculated from the wellknown formulas

$$\text{Power} = VI \quad \text{and} \quad \text{Energy} = VIt$$

However, the energy of the chemical input and output is not so easily defined. At a simple level we could say that it is the ‘chemical energy’ of the H₂, O₂, and H₂O that is in question. The problem is that ‘chemical energy’ is not simply defined – and terms such as enthalpy, Helmholtz function, and Gibbs free energy are used.

In the case of fuel cells, it is the ‘Gibbs free energy’ that is important. This can be defined as the ‘energy available to do external work.’

When working with chemical reactions, the zero energy point is normally defined as pure elements, in the normal state, at standard temperature and pressure (25°C, 0.1 MPa). The term ‘Gibbs free energy of formation’, G_f , rather than the ‘Gibbs free energy’ is used when adopting this convention.

In a fuel cell, it is the change in the Gibbs free energy of formation, ΔG_f , that gives us the energy released. This change is the difference between the Gibbs free energy of the products and the Gibbs free energy of the inputs or reactants. [20]

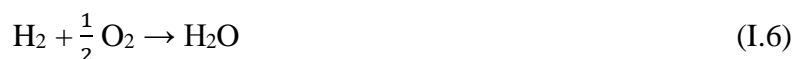
$$\Delta G_f = G_f \text{ of products} - G_f \text{ of reactants}$$

To make comparisons easier, it is nearly always most convenient to consider these quantities in their ‘per mole’ form. These are indicated by over the lower case letter, for example, $(\bar{g}_f)_{\text{H}_2\text{O}}$ is the molar specific Gibbs free energy of formation for water.

Consider the basic reaction for the hydrogen/oxygen fuel cell:



which is equivalent to



The ‘product’ is one mole of H_2O and the ‘reactants’ are one mole of H_2 and half a mole of O_2 . Thus,

$$\Delta \bar{g}_f = \bar{g}_f \text{ of products} - \bar{g}_f \text{ of reactants}$$

So we have

$$\Delta \bar{g}_f = (\bar{g}_f)_{\text{H}_2\text{O}} - (\bar{g}_f)_{\text{H}_2} - \frac{1}{2} (\bar{g}_f)_{\text{O}_2} \quad (\text{I.7})$$

This equation seems straightforward and simple enough. However, the Gibbs free energy of formation is not constant; it changes with temperature and state (liquid or gas).

Table below shows \bar{g}_f for the basic hydrogen fuel cell reaction at various temperatures.

Form of water product	Temperature (°C)	$\Delta \bar{g}_f$ (kJ mol ⁻¹)
Liquid	25	-237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

Table I.2 . $\Delta \bar{g}_f$ for the reaction $\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$

Note that the values are negative, which means that energy is released.

If there are no losses in the fuel cell, or as we should more properly say, if the process is ‘reversible’, then all this Gibbs free energy is converted into electrical energy. (In practice, some is also released as heat.) We will use this to find the reversible OCV of a

fuel cell. [16]

For one mole of hydrogen used, $2N$ electrons pass round the external circuit – where N is Avogadro's number. If $-e$ is the charge on one electron, then the charge that flows is

$$2Ne = -2F \text{ coulombs} \quad (\text{I.9})$$

F being the Faraday constant, or the charge on one mole of electrons.

If E is the voltage of the fuel cell, then the electrical work done moving this charge round the circuit is

Electrical work done = charge \times voltage = $-2FE$ joules

If the system is reversible (or has no losses), then this electrical work done will be equal to the Gibbs free energy released $\Delta\bar{g}_f$. So

$$\Delta\bar{g}_f = -2FE \quad (\text{I.10})$$

Thus

$$E = \frac{-\Delta\bar{g}_f}{2F} \quad (\text{I.11})$$

This fundamental equation gives the electromotive force (EMF) or reversible open circuit voltage of the hydrogen fuel cell [16]

For example, a hydrogen fuel cell operating at 200°C has $\Delta\bar{g}_f = -220 \text{ kJ}$, so

$$(\text{I.12}) \quad E = \frac{220000}{2 \times 96485} = 1.14 \text{ V}$$

I.7 Polymer electrolyte membrane:

To function, the membrane must conduct hydrogen ions (protons) but not electrons as this would in effect "short circuit" the fuel cell. The membrane must also not allow either gas to pass to the other side of the cell, a problem known as **gas crossover**. Finally, the membrane must be resistant to the reducing environment at the cathode as well as the harsh oxidative environment at the anode.

Splitting of the hydrogen molecule is relatively easy by using a platinum catalyst. Unfortunately however, splitting the oxygen molecule is more difficult, and this causes significant electric losses. An appropriate catalyst material for this process has not been discovered, and platinum is the best option. [16]

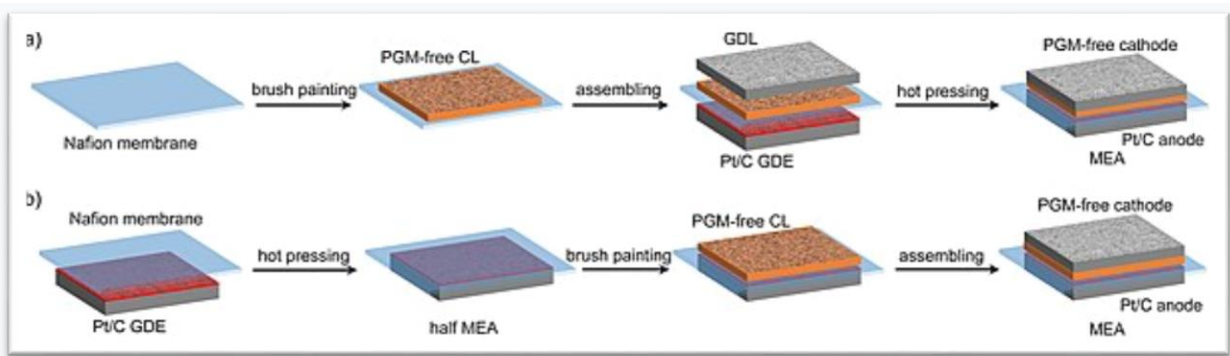


Figure I.9. MEA fabrication methods for PEMFC

I.8 Gas diffusion layer:

The GDL electrically connects the catalyst and current collector. It must be porous, electrically conductive, and thin. The reactants must be able to reach the catalyst, but conductivity and porosity can act as opposing forces. Optimally, the GDL should be composed of about one third Nafion or 15% PTFE. The carbon particles used in the GDL can be larger than those employed in the catalyst because surface area is not the most important variable in this layer. GDL should be around 15–35 μm thick to balance needed porosity with mechanical strength. Often, an intermediate porous layer is added between the GDL and catalyst layer to ease the transitions between the large pores in the GDL and small porosity in the catalyst layer. Since a primary function of the GDL is to help remove water, a product, flooding can occur when water effectively blocks the GDL. This limits the reactants ability to access the catalyst and significantly decreases performance. Teflon can be coated onto the GDL to limit the possibility of flooding. Several microscopic variables are analyzed in the GDLS such as: porosity, tortuosity and permeability. These variables have incidence over the behavior of the fuel cells.[24]

I.9 Efficiency:

The maximal theoretical efficiency applying the Gibbs free energy equation $\Delta G = -237.13$ kJ/mol and using the heating value of Hydrogen ($\Delta H = -285.84$ kJ/mol) is 83% at 298 K.

The practical efficiency of a PEMs is in the range of 50–60% . Main factors that create losses are:

- Activation losses
- Ohmic losses
- Mass transport losses

I.9 Water management for pem fuel cell:

One of the greatest challenges associated with PEMFCs is the water balance in the fuel cell stack. As the chemical reaction occurs in each cell, water is generated. Depending upon the load and the operating conditions, there is a tendency for the fuel cells to both flood and dry-out. The water content in the **polymer membrane** affects the proton conductivity and affects activation overpotentials. If the **MEA** is not adequately humidified, the protonic conductivity decreases, which means that the cell resistance increases.

Excess water can create an issue in fuel cells. It can prevent reactant diffusion to the **catalyst** sites by flooding of the **electrodes**, gas diffusion backings, or gas channels if the water removal is inefficient. For the membrane to remain hydrated, parameters such as current density, temperature, reactant flow rates, pressures, humidification, cell design, and component materials need to be optimized. Water in a PEM fuel cell arises due to the cathode reaction and the humidification of the reactant gases. The water production in the cathode depends upon the current density (the current being drawn by the load). Water buildup in a fuel cell can be mitigated through the **gas diffusion layer**, flow channel or heater design.

Water is transported mainly through the gas channels, but also through the membrane and the electrodes. Two transport processes that occur in the polymer membrane are diffusion and the electro-osmotic drag:[16]

I.9.1 Electro-osmotic drag: happens when hydrogen protons travel through the polymer membrane from the anode to the cathode and carry water molecules with them. The average number of water molecules “dragged” by a single proton is called the electro osmotic drag coefficient .

I.9.2 Back diffusion: occurs when the concentration gradient in the cathode drives the diffusion of water through the membrane.

The accumulation of water at the cathode occurs from both the electro-osmotic drag and the production of water at the cathode. The water at the cathode can be either transported to the flow channel through the gas diffusion backing, evaporated through heaters, or diffused through the membrane towards the anode.[26]

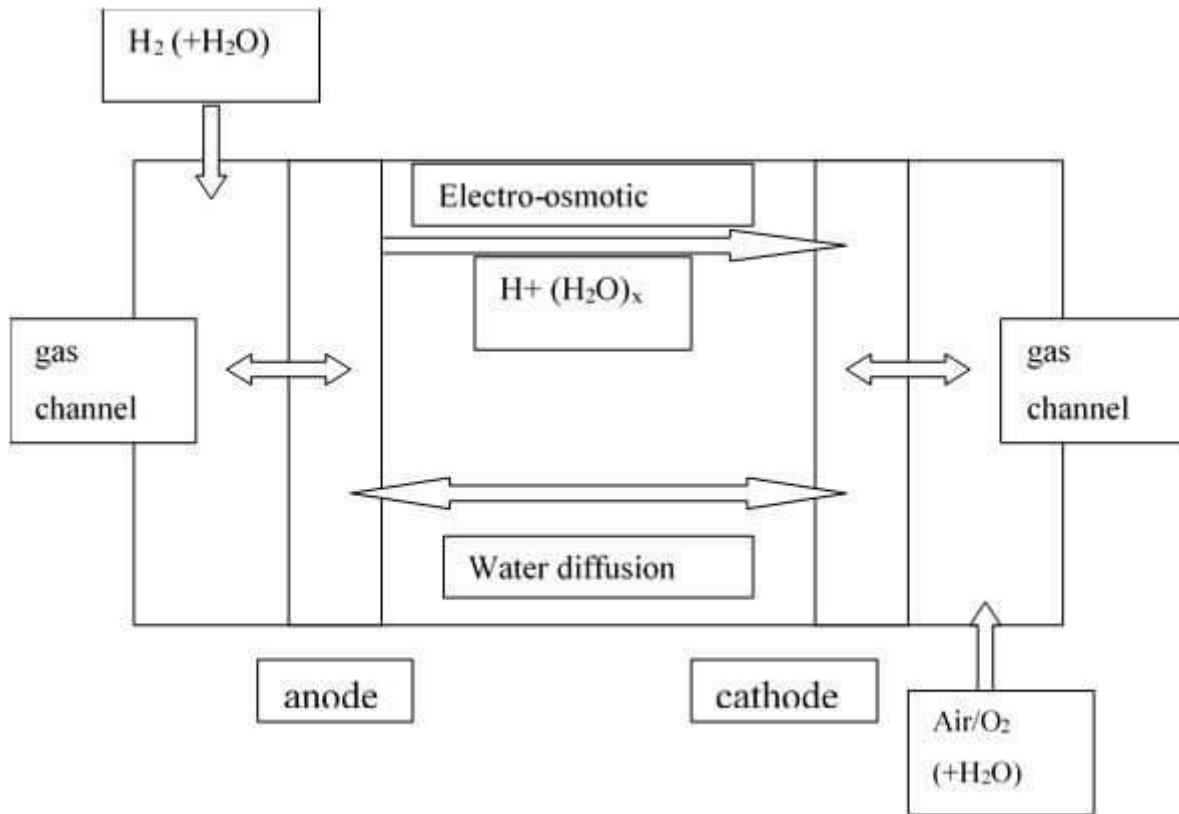


figure I.10. Water transport processes in a PEM fuel cell

Water can be removed from a PEM fuel cell is through the reactant streams. Undersaturated reactant gases pick up the liquid water in the flow channels. The water removal rate and the ratio of liquid and gaseous water depend upon the operating conditions and cell design. The operating temperature, pressure and flow rates have a substantial effect on water vapor content of the gases, water evaporation rate and vapor pressure. Therefore, the efficiency of water removal depends upon these parameters. The ratio of liquid and gaseous water is determined by the operating temperature and the humidity of input reactant gases.

I.10 PEMFC Air-Feed System Model:

It is clear from the above discussion that the power generation inside the PEMFC core depends upon several variables and factors, such as oxygen and hydrogen pressures, temperature and various physical parameters of the fuel cell. All these must be controlled rigorously for proper and safe operation of the fuel cell. Hence an operational PEMFC system contains the fuel cell core and a certain number of auxiliary systems for control .

The aim of the air-feed system is to regulate the oxygen quantity in the cathode. It usually consists of an electromechanical air compressor that maintains the required oxygen pressure and mass-flow in the cathode of PEMFC.

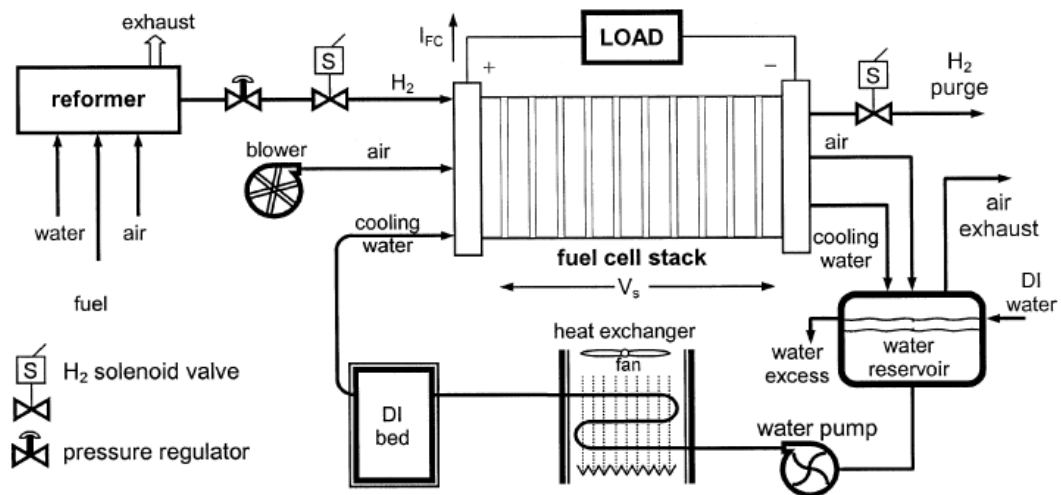


Figure I.11. Fuel cell system scheme

this system can consume up to 30% of the fuel cell power and requires precise control in order to optimize the net power output of the PEMFC system. This system has been modeled under the following assumptions:

- All gases obey the ideal gas law;
- The temperature of the air inside the cathode is equal to the stack temperature, also is equal to the temperature of the coolant exiting the stack. The stack temperature is well controlled;
- The input reactant flows are humidified in a consistent and rapid way and the high pressure compressed hydrogen is available;
- The water inside the cathode is only in vapor phase and any extra water in liquid phase is removed from the channels; [27]

I.11 Strengths:

The PEMFC is a prime candidate for vehicle and other mobile applications of all sizes down to mobile phones, because of its compactness.

I.12 Weaknesse:

Fuel Cells based on PEM still have many issues:

I.12.1 Vulnerability of the Catalyst:

The platinum catalyst on the membrane is easily poisoned by carbon monoxide, which is often present in product gases formed by methane reforming (no more than one part per million is usually acceptable). This generally necessitates the use of the water gas shift reaction to eliminate CO from product gases and form more hydrogen. Additionally, the membrane is sensitive to the presences of metal ions, which may impair proton conduction mechanisms and can be introduced by corrosion of metallic bipolar plates, metallic components in the fuel cell system or from contaminants in the fuel/oxidant.

PEM systems that use reformed methanol were proposed, as in Daimler Chrysler Nocar 5; reforming methanol, i.e. making it react to obtain hydrogen, is however a very complicated

process, that requires also purification from the carbon monoxide the reaction produces. A platinum-ruthenium catalyst is necessary as some carbon monoxide will unavoidably reach the membrane. The level should not exceed 10 parts per million. Furthermore, the start-up times of such a reformer reactor are of about half an hour. Alternatively, methanol, and some other biofuels can be fed to a PEM fuel cell directly without being reformed, thus making a direct methanol fuel cell (DMFC). These devices operate with limited success.[16]

I.13 PEM Fuel Cell Applications:

Many industries are pushing for fuel cells to be used in portable electronic devices. These devices are getting smaller and more powerful, with; internet /phone /messaging /radio /music /TV /video /camera /photos /games /documents /3G /Bluetooth /GPS /; these devices need a lot of power, to last an acceptable period of time, in a small space. PEM fuel cells are not readily available in the market place but Direct Methanol Fuel Cells (DMFC), have been pioneered by some companies due to the availability of their fuel, methanol. Angstrom Power Inc. is one of many new companies and has demonstrated ‘Better than Batteries’ performance at scales equivalent to today's mobile lithium ion batteries. Toshiba launched a direct methanol fuel cell in Japan in October 2009 as an external power source for mobile electric devices .

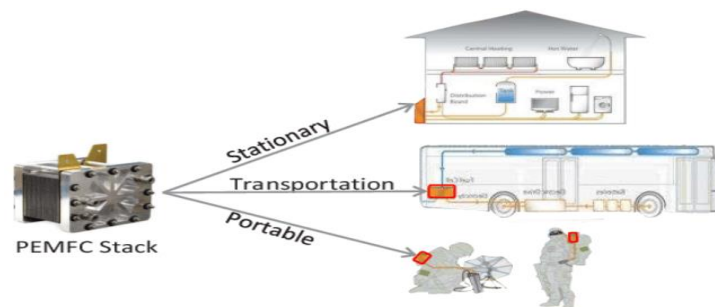


Figure I.12.PEM Fuel Cell applications

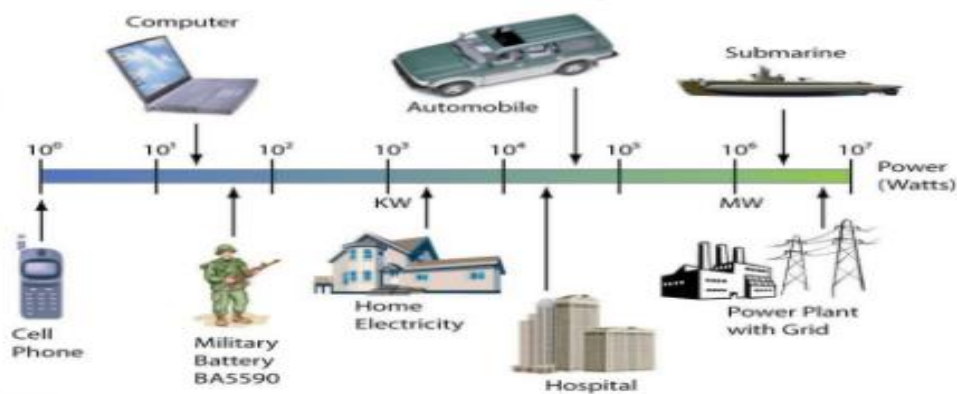


Figure I.13 .The types of fuel cell applications

Advantages

The most important disadvantage of fuel cells at the present time is the same for all types – the cost. However, there are varied advantages, which feature more or less strongly for different types and lead to different applications .These include the following:

- *Efficiency.* As is explained in the following chapter, fuel cells are generally more efficient than combustion engines whether piston or turbine based. A further feature of this is that small systems can be just as efficient as large ones. This is very important in the case of the small local power generating systems needed for combined heat and power systems.
- *Simplicity.* The essentials of a fuel cell are very simple, with few if any moving parts. This can lead to highly reliable and long-lasting systems.
- *Low emissions.* The by-product of the main fuel cell reaction, when hydrogen is the fuel, is pure water, which means a fuel cell can be essentially 'zero emission'. This is their main advantage when used in vehicles, as there is a requirement to reduce vehicle emissions, and even eliminate them within cities. However, it should be noted that, at present, emissions of CO₂ are nearly always involved in the production of hydrogen that is needed as the fuel.
- *Silence.* Fuel cells are very quiet, even those with extensive extra fuel processing equipment. This is very important in both portable power applications and for local power generation in combined heat and power schemes.

II.14 conclusion:

in this chapter , we present the main topics of PEM-FC, where we have presented its history,its main element and its applications.

Chapter II:

PEM Fuel cell emulator

II. Introduction:

The PEM-FC emulator contains many parts to reach the wanted result, in this chapter we will define the components needed to make a PEM fuel cell emulator also we will define its characteristics

II.2 The emulator:

Emulation is one strategy in pursuit of digital preservation and combating obsolescence. Emulation focuses on recreating an original computer environment, which can be time-consuming and difficult to achieve, but valuable because of its ability to maintain a closer connection to the authenticity of the digital object, operating system, or even gaming platform. Emulation addresses the original hardware and software environment of the digital object, and recreates it on a current machine.[29] The emulator allows the user to have access to any kind of application or operating system on a current platform, while the software runs as it did in its original environment. Jeffery Rothenberg, an early proponent of emulation as a digital preservation strategy states, "the ideal approach would provide a single extensible, long-term solution that can be designed once and for all and applied uniformly, automatically, and in organized synchrony (for example, at every refresh cycle) to all types of documents and media".[23] He further states that this should not only apply to out of date systems, but also be upwardly mobile to future unknown systems. Practically speaking, when a certain application is released in a new version, rather than address compatibility issues and migration for every digital object created in the previous version of that application, one could create an emulator for the application, allowing access to all of said digital objects [30]

Most emulators just emulate a hardware architecture—if operating system firmware or software is required for the desired software, it must be provided as well (and may itself be emulated). Both the OS and the software will then be interpreted by the emulator, rather than being run by native hardware. Apart from this interpreter for the emulated binary machine's language, some other hardware (such as input or output devices) must be provided in virtual form as well; for example, if writing to a specific memory location should influence what is displayed on the screen, then this would need to be emulated. While emulation could, if taken to the extreme, go down to the atomic level, basing its output on a simulation of the actual circuitry from a virtual power source, this would be a highly unusual solution. Emulators typically stop at a simulation of the documented hardware specifications and digital logic. Sufficient emulation of some hardware platforms requires extreme accuracy, down to the level of individual clock cycles, undocumented features, unpredictable analog elements, and implementation bugs. We will take for example "the PEM fuel cell emulator"

II.2.1 Benefits:

- Potentially better graphics quality than original hardware.
- Potentially additional features original hardware didn't have.
- Emulators maintain the original look, feel, and behavior of the digital object, which is just as important as the digital data itself.

- Despite the original cost of developing an emulator, it may prove to be the more cost efficient solution over time.
- Reduces labor hours, because rather than continuing an ongoing task of continual data migration for every digital object, once the library of past and present operating systems and application software is established in an emulator, these same technologies are used for every document using those platforms.
- Many emulators have already been developed and released under the GNU General Public License through the open source environment, allowing for wide scale collaboration.
- Emulators allow software exclusive to one system to be used on another.

II.3 Fuel Cell Emulator:

The PEM-FC have four main principal containt , as presented in figure (II.1):

- The PEM-FC model
- The DC-DC buck converter
- The PID regulator
- The PWM generator

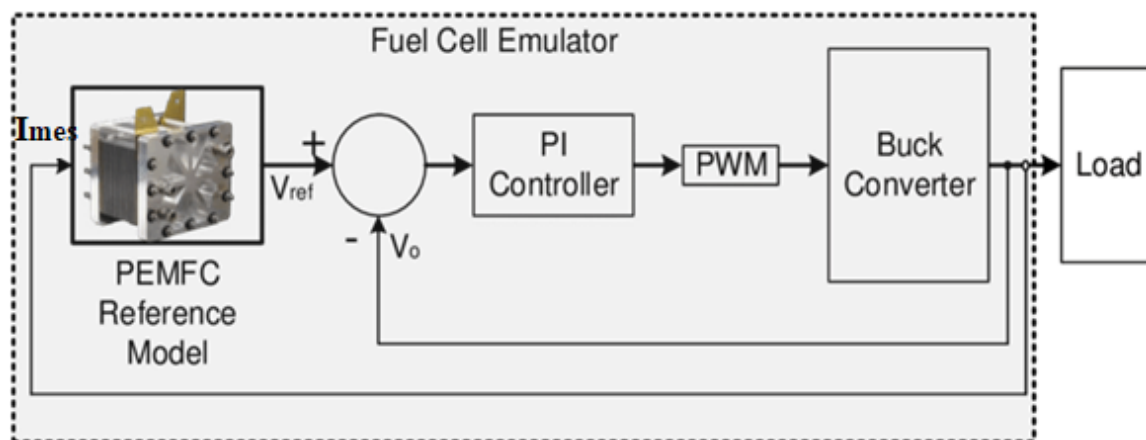


Figure. II.1: Emulator block diagram .

III.3.1 the PEM-FC model :

The output voltage of a single cell can be defined as the result of the following expression [24],

$$V_{FC} = E_{Nernst} - V_{ohmic} - V_{act} - V_{con}$$

In the equation above, E_{Nernst} is the thermodynamic potential of the cell and it represents its reversible voltage; V_{act} is the voltage drop due to the activation of the anode and cathode (also known as activation over potential), a measure of the voltage drop associated with the electrodes; V_{ohmic} is the ohmic voltage drop (also known as ohmic over potential), a measure of the ohmic voltage drop resulting from the resistances of the conduction of protons through the solid electrolyte and the electrons through its path; and V_{con} represents the voltage drop resulting from the reduction in concentration of the reactants gases or, alternatively, from the transport of mass of oxygen and hydrogen (also known as concentration over potential). There is another voltage drop associated with the internal currents and/or the fuel crossover. This voltage drop is considered in the model, using affixed current density even at no-load operation (represented by J_n). The first term of (4) represents the FC open-circuit voltage (without load), while the last three terms represent reductions in this voltage to supply the useful voltage across the cell electrodes V_{FC} for a certain operation current. Each one of the terms of (4) is discussed and modeled separately in the sections that follow. Also, the following sections show the dynamic behavior of FCs and the equations for electrical power generation. For fuel cell emulator [41], E_{cell} is the open circuit voltage of the cell and it is higher than the cell output voltage of the cell effect by losses which are activation losses, ohmic losses, and concentration losses. For fuel cell emulator, the topology consists of passive semiconductor components such as resistor and capacitor. The output voltage of fuel cell stack can be calculated by; [25]

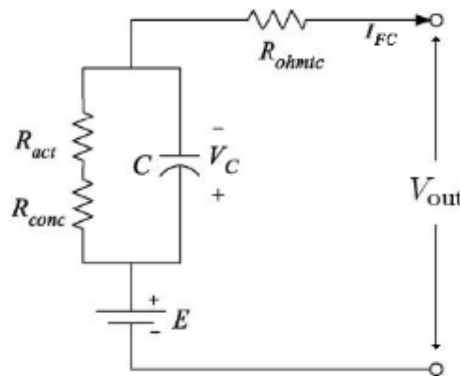


Figure II.2: Equivalent electrical circuit of PEMFC

E = Open Circuit Voltage

V_{act} = Activation Losses Voltage

V_{con} = Ohmic Losses Voltage

V_{ohmic} = Concentration Losses Voltage

N_{cell} = Number of Cell

.

II.3.1.1 Partial pressure: [25]

Partial pressure of hydrogen:

$$P_{H_2} = 0.5 * P_{H_2O^{sat}} \left[e^{\frac{-1.635J}{T^{1.334}}} * \left(\frac{P_a}{P_{H_2O^{sat}}} \right) - 1 \right] \quad (II.1)$$

Partial pressure of oxygen:

$$P_{O_2} = P_{H_2O^{sat}} \left[e^{\frac{-4.192J}{T^{1.334}}} * \left(\frac{P_c}{P_{H_2O^{sat}}} \right) - 1 \right] \quad (II.2)$$

Where:

P_c : partial pressure for cathode.

$P_{H_2O^{sat}}$: saturation pressure for water.

P_a : partial pressure for anode.

- **saturation pressure for water:**

$$\log_{10} P_{H_2O^{sat}} = -2.18 + 2.95 * 10^{-5} T_c - 9.18 * 10^{-5} T_c^2 + 1.44 * 10^{-7} T_c^3 \quad (II.3)$$

$$T_c = T - 273.15 \quad (II.4)$$

II.3.1.2 Cell Reversible Voltage:

The reversible voltage of the cell (E_{Nernst}) is the potential of the cell obtained in an open circuit thermodynamic balance (without load). In this model, E_{Nernst} is calculated starting from a modified version of the equation of Nernst, with an extra term to take into account changes in the temperature with respect to the standard reference temperature, 25C [24]. This is given by

$$E_{Nernst} = \frac{\Delta G}{2.F} + \frac{\Delta S}{2.F} (T - T_{ref}) + \frac{R.T}{2.F} \cdot \left[\ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2}) \right] \quad (II.5)$$

Where ΔG is the change in the free Gibbs energy (J/mol); F is the constant of Faraday (96.487 C); ΔS is the change of the entropy (J/mol); R is the universal constant of the gases (8.314 J/K.mol); while P_{H_2} and P_{O_2} are the partial pressures of hydrogen and oxygen (atm), respectively. Variable T denotes the cell operation temperature (K) and T_{ref} the reference temperature. Using the standard pressure and temperature (SPT) values for ΔG , ΔS and, T_{ref} (5) can be simplified to

$$E_{Nernst} = 1.229 - 0.85 \cdot 10^{-3} \cdot (T - 298.15) + 4.31 \cdot 10^{-5} \cdot T \cdot \left[\ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2}) \right]. \quad (II.6)$$

It has to be noted that membrane temperature and gases partial pressures change with cell current: with increasing current, partial pressure of hydrogen or oxygen decreases, whereas temperature increases [24]

II.3.1.3 Activation Voltage Drop:

the activation overpotential, including anode and cathode, can be calculated by

$$V_{act} = -[\xi_1 + \xi_2 \cdot T + \xi_3 \cdot T \ln(C_{O_2}) + \xi_4 \cdot T \cdot \ln(i_{FC})] \quad (II.7)$$

Where i_{FC} is the cell operating current (A), and the ξ 's represent parametric coefficients for each cell model, whose values are defined based on theoretical equations with kinetic, thermodynamic, and electrochemical foundations [24]. C_{H_2} and C_{O_2} are concentration of hydrogen and oxygen (mol/cm^2).

$$C_{O_2} = \frac{P_{O_2}}{5.08 \cdot 10^6 \cdot e^{\left(\frac{-498}{T}\right)}} \quad (II.8)$$

$$C_{H_2} = P_{H_2} \cdot 9.17 \cdot 10^{-7} \cdot e^{-77/T} \quad (II.9)$$

II.3.1.4 Ohmic Voltage Drop:

The **ohmic** voltage drop results from the resistance to the electrons transfer through the collecting plates and carbon electrodes, and the resistance to the protons transfer through the solid membrane. In this model, a general expression for resistance is defined to include all the important parameters of the membrane. The equivalent resistance of the membrane is calculated by [24]

$$R_M = \frac{\rho M \cdot l}{A} \quad (II.10)$$

The following numeric expression for the resistivity of the Nafion membranes is used [1]:

$$\rho M = \frac{181.6 \cdot [1 + 0.03 \cdot \left(\frac{i_{FC}}{A}\right) + 0.062 \cdot \left(\frac{T}{303}\right)^2 \cdot \left(\frac{i_{FC}}{A}\right)^{2.5}]}{\left[\psi - 0.643 - 3 \cdot \left(\frac{i_{FC}}{A}\right)\right] \cdot e^{4.18 \cdot \left(\frac{T-303}{T}\right)}} \quad (II.11)$$

Using the value of (10) for the membrane resistance, the following expression determines the ohmic voltage drop:

$$V_{ohmic} = i_{FC} \cdot (R_M + R_C) \quad (II.12)$$

II.3.1.5 Concentration Or Mass Transport Voltage Drop:

The mass transport affects the concentrations of hydrogen and oxygen. This, in turn, causes a decrease of the partial pressures of these gases. Reduction in the pressures of oxygen and hydrogen depend on the electrical current and on the physical characteristics of the system. To determine an equation J_{max} for this voltage drop, a maximum current density is defined, under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for J_{max} are in the range of 500–1500 (mA/cm^2). Thus, the voltage drop due to the mass transport can be determined by: [24]

$$V_{con} = -B \cdot \ln\left(1 - \frac{J}{J_{max}}\right) \quad (II.13)$$

J Represents the actual current density of the cell (A/cm^2) can be determined by.

$$J = \frac{i_{FC}}{A} \quad (II.14)$$

II.3.2 dc-dc converter:

Every Electronic circuit is assumed to operate some supply voltage which is usually assumed to be constant in nature. A voltage regulator is a power electronic circuit that maintains a constant output voltage irrespective of change in load current or line voltage. Many different types of voltage regulators with a variety of control schemes are used. With the increase in circuit complexity and improved technology a more severe requirement for accurate and fast regulation is desired. This has led to need for newer and more reliable design of dc-dc converters. The dc-dc converter inputs an unregulated dc voltage input and outputs a constant or regulated voltage. The regulators can be mainly classified into linear and switching regulators. All regulators have a power transfer stage and a control circuitry to sense the output voltage and adjust the power transfer stage to maintain the constant output voltage. Since a feedback loop is necessary to maintain regulation, some type of compensation is required to maintain loop stability. Compensation techniques vary for different control schemes and a small signal analysis of system is necessary to design a stable compensation circuit. State space analysis is typically used to develop a small signal model of a converter and then depending on the type of control scheme used, the small signal model of converter is modified to facilitate the design of the compensation network. In contrast to a state space approach, PWM switch modeling develops a small signal of switching components of converter. [16]

II.3.2.1 Applications of DC-DC Converters:

Dc converters can be used in regenerative braking of dc motors to return energy back into the supply and this feature results in energy savings for transportation system with frequent stops. As for example :

- a) Traction motor control in electric automobiles
- b) Trolley cars
- c) Marine Hoists
- d) Forklift trucks
- e) Mine Haulers

2. Also they used in DC voltage regulators and also they are used in conjunction with an inductor to generate a dc current source especially for the current source inverter. [16]

II.3.2.2 Switching Consideration of DC-DC Converters:

The converter switch can be implemented by using :

- a) Power bipolar junction transistor (BJT)
- b) Power Metal Oxide Semiconductor Field Effect Transistor (MOSFET)
- c) Gate Turn Off Thyristor (GTO)

d) Insulated gate bipolar transistor (IGBT)

Practical devices have a finite voltage drop ranging from 0.5V to 2V but during the calculations for the sake of simplicity of the understanding, these switches are considered lossless.

II.3.2.3 Types Of DC-DC Converter:

There different kinds of DC-DC converters. A variety of the converter names are included here:

- The BUCK converter
- The BOOST converter
- The BUCK-BOOST converter
- The CUK converter
- The Fly-back converter
- The Forward Converter
- The Push-pull Converter
- The Full Bridge converter
- The Half Bridge Converter
- Current Fed converter

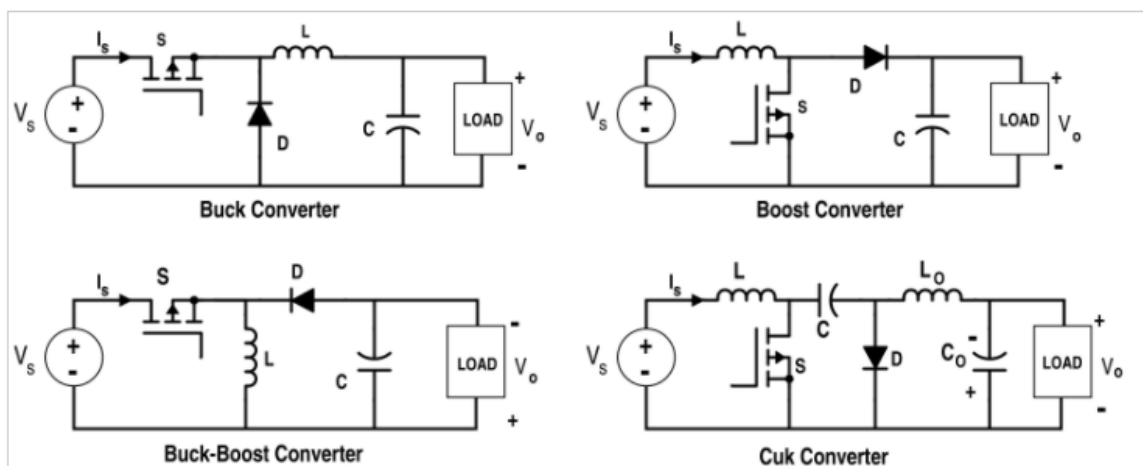


Figure II.3. basic dc-dc converter

II.3.2.4 Study of DC-DC Converters:

There are a variety of DC-Dc converters are possible.in this manuscript we focus only on the DC-DC buck converter wich is used in PEM-FC emulator as power part.

II.3.2.5 The Buck Converter:

The buck converter is a commonly used in circuits that steps down the voltage level from the input voltage according to the requirement. It has the advantages of simplicity and low cost. Figure 1 shows a buck converter the operation of the Buck converters start with a switch that is open (so no current flow through any part of circuit) When the switch is closed, the current flows through the inductor, slowly at first, but building up over time. When the switch is closed the inductor pulls current through the diode, and this means the voltage at the inductors "output" is lower than it first was. This is the very basic principle of operation of buck circuit.[16]

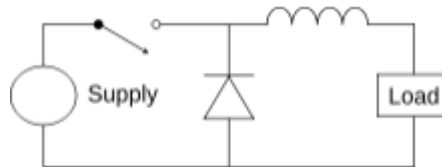


Figure II.4. BUCK Converter

II.3.2.6 Analysis of the buck converter begins by making these assumptions:

1. The circuit is operating in the steady state.
2. The inductor current is continuous(always positive)
3. The capacitor is very large, and the output voltage is held constant at voltage V_o . This restriction will be relaxed later to show the effects of finite capacitance.
4. The switching period is T , the switch is closed for time $D.T$ and open for time $(1- D)T$.
D: duty cycl
5. The components are ideal .

The key to the analysis for determining the voltage V_o (output voltage of DC DC buck converter) is to examine the inductor current and inductor voltage first for the switch closed and then for the switch open. The net change in inductor current over one period must be zero for steady state operation. The average inductor voltage is zero. There are two types of operational mode for this circuit a) Continuous Conduction Mode and b) Discontinuous Conduction Mode. They are described below. [16]

II.3.2.7 Continuous Conduction Mode:

A buck converter operates in continuous mode if the current through the inductor (I_L) never falls to zero during the commutation cycle. In this mode, the operating principle is described by the chronogram in Figure 1.

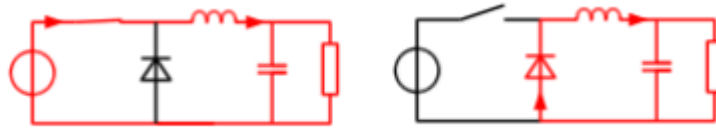


Figure. II.5. The two circuit configurations of a buck converter: (a) On-state, when the switch is closed, and (b) Off-state, when the switch is open

- When the switch pictured above is closed (On-state, top of Figure 2), the voltage across the inductor is $V_L = V_i - V_o$. The current through the inductor rises linearly. As the diode is reverse-biased by the voltage source V , no current flows through it;
- When the switch is opened (off state, bottom of figure 2), the diode is forward biased. The voltage across the inductor is $V_L = -V_o$ (neglecting diode drop). Current I_L decreases.

The energy stored in inductor L is:

$$E = \frac{1}{2}L \times I_L^2 \quad (\text{II.15})$$

Therefore, it can be seen that the energy stored in L increases during On-time (as I_L increases) and then decreases during the Off-state. L is used to transfer energy from the input to the output of the converter. The rate of change of I_L can be calculated from:

$$V_L = L \frac{dI_L}{dt} \quad (\text{II.16})$$

With V_L equal to $V_i - V_o$ during the On-state and to $-V_o$ during the Off-state. Therefore, the increase in current during the On-state is given by:

$$\Delta I_{Lon} = \int_0^{t_{off}} \frac{V_L}{L} dt = -\frac{(V_i - V_o)}{L} t_{on} \quad t\{on\} = DT \quad (\text{II.17})$$

Identically, the decrease in current during the Off-state is given by:

$$\Delta I_{Loff} = \int_{t_{on}}^{t_{off}} \frac{V_L}{L} dt = -\frac{V_o}{L} t_{off} \quad t\{off\} = T \quad (\text{II.18})$$

If we assume that the converter operates in steady state, the energy stored in each component at the end of a commutation cycle T is equal to that at the beginning of the cycle. That means that the current I_L is the same at $t=0$ and at $t=T$ (see Figure 3). So we can write from the above equations:

$$\frac{(V_i - V_0)}{L} t_{on} - \frac{V_0}{L} t_{off} = 0 \quad (\text{II.19})$$

It is worth noting that the above integrations can be done graphically: In Figure 18, $\Delta I_{L_{on}}$ is proportional to the area of the yellow surface, $\Delta I_{L_{on}}$ and to the area of the orange surface, as these surfaces are defined by the inductor voltage (red) curve. As these surfaces are simple rectangles, their areas can be found easily: $(V_i - V_0)$ for the yellow rectangle and $-V_0 T_{off}$ for the orange one. For steady state operation, these areas must be equal. As can be seen on figure 18, $t_{on} = DT$ and $t_{off} = (1 - D)T$. D is a scalar called the duty cycle with a value between 0 and 1. This yields:

$$\begin{aligned} (V_i - V_0)DT - V_0(1 - D)T &= 0 \\ \rightarrow V_0 - DV_i &= 0 \\ \rightarrow D &= \frac{V_0}{V_i} \end{aligned} \quad (\text{II.20})$$

From this equation, it can be seen that the output voltage of the converter varies linearly with the duty cycle for a given input voltage. As the duty cycle D is equal to the ratio between t_{on} and the period T , it cannot be more than 1. ($V_i \leq V_0$) Therefore, . This is why this converter is referred to as step-down converter. So, for example, stepping 12 V down to 3 V (output voltage equal to a fourth of the input voltage) would require a duty cycle of 25%, in our theoretically ideal circuit.

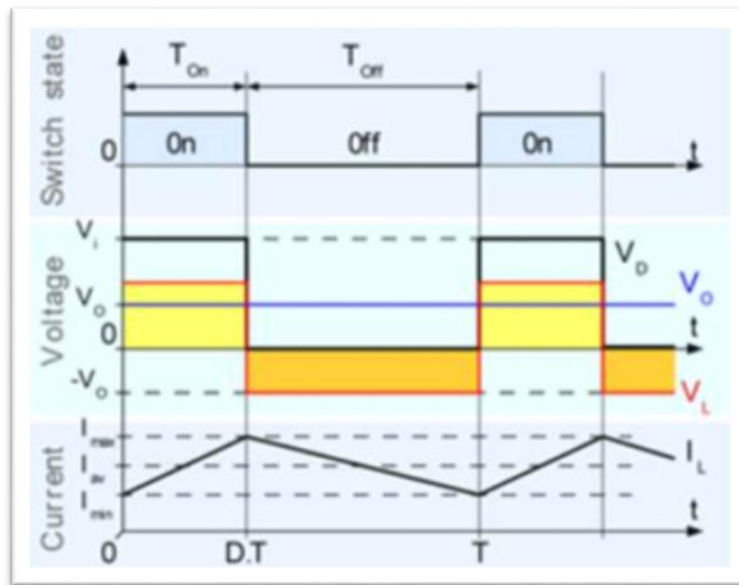


Figure II.6. Evolution of the voltages and currents in an ideal buck converter operating in continuous mode

II.3.2.8 Discontinuous Conduction Mode:

In some cases, the amount of energy required by the load is small enough to be transferred in a time lower than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (Figure 4). This has, however, some effect on the previous equations.[16]

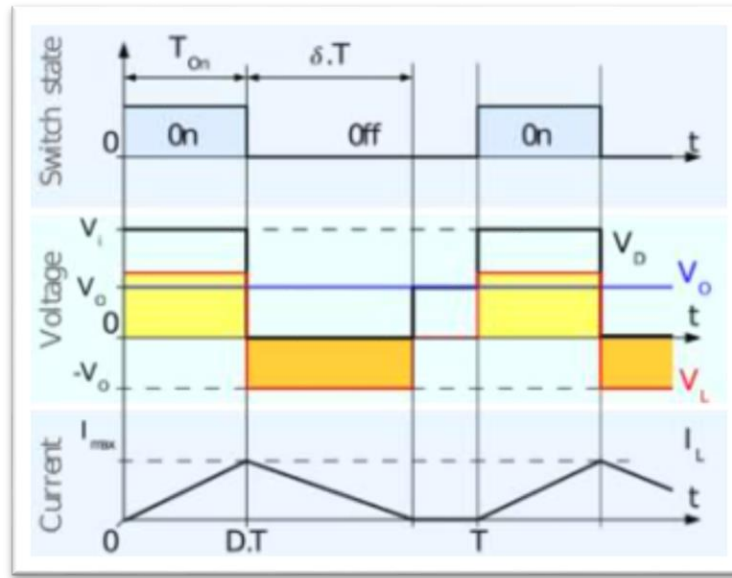


figure II.7. Evolution of the voltages and currents in an ideal buck converter operating in discontinuous mode.

We still consider that the converter operates in steady state. Therefore, the energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero). This means that the average value of the inductor voltage (V_L) is zero; i.e., that the area of the yellow and orange rectangles in figure 5 are the same. This yields:

$$(V_i - V_o)DT - V_o\delta T = 0 \quad (\text{II.21})$$

So the value of δ is:

$$\delta = \frac{(V_i - V_o)}{V_o} D \quad (\text{II.22})$$

The output current delivered to the load (I_o) is constant; as we consider that the output capacitor is large enough to maintain a constant voltage across its terminals during a commutation cycle. This implies that the current flowing through the capacitor has a zero average value. Therefore, we have: $\bar{I}_L = I_o$

Where \bar{I}_L is the average value of the inductor current. As can be seen in figure 5, the inductor current waveform has a triangular shape. Therefore, the average value of I_L can be sorted out geometrically as follow:

$$\bar{I}_L = \left(\frac{1}{2} I_{Lmax} DT + \frac{1}{2} I_{Lmax} \delta T \right) \frac{1}{T} \quad (\text{II.23})$$

$$\bar{I}_L = \frac{I_{Lmax}(D+\delta)}{2}$$

$$\bar{I}_L = I_0$$

The inductor current is zero at the beginning and rises during t_{on} up to I_{Lmax} . That means that I_{Lmax} is equal to:

$$I_{Lmax} = \frac{(V_i - V_0)}{L} DT \quad (\text{II.24})$$

Substituting the value of I_{Lmax} in the previous equation leads to:

$$I_0 = \frac{(V_i - V_0)DT(D+\delta)}{2L} \quad (\text{II.25})$$

And substituting δ by the expression given above yields:

$$I_0 = \frac{(V_i - V_0)DT \left(D + \frac{(V_i - V_0)D}{V_0} \right)}{2L} \quad (\text{II.26})$$

This expression can be rewritten as:

$$V_0 = V_i \frac{1}{\frac{2LI_0}{D^2 V_i T} + 1} \quad (\text{II.27})$$

It can be seen that the output voltage of a buck converter operating in discontinuous mode is much more complicated than its counterpart of the continuous mode. Furthermore, the output voltage is now a function not only of the input voltage (V_i) and the duty cycle D , but also of the inductor value (L), the commutation period (T) and the output current (I_0). [16]

II.3.3 PID Controller:

A **PID controller** is an instrument used in industrial control applications to regulate temperature, flow, pressure, speed and other process variables. PID (proportional integral derivative) controllers use a control loop feedback mechanism to control process variables and are the most accurate and stable controller. PID control is a well-established way of driving a system towards a target position or level. It's a practically ubiquitous as a means of controlling temperature and finds application in myriad chemical and scientific processes as well as automation. PID control uses closed-loop control feedback to keep the actual output from a process as close to the target or setpoint output as possible.

II.3.3.1 PID Controller Working Principle:

The working principle behind a PID controller is that the proportional, integral and derivative terms must be individually adjusted or "tuned." Based on the difference between these values a

correction factor is calculated and applied to the input. For example, if an oven is cooler than required, the heat will be increased. Here are the three steps:

- **Proportional tuning:** involves correcting a target proportional to the difference. Thus, the target value is never achieved because as the difference approaches zero, so too does the applied correction.
- **Integral tuning:** attempts to remedy this by effectively cumulating the error result from the "P" action to increase the correction factor. For example, if the oven remained below temperature, "I" would act to increase the heat delivered. However, rather than stop heating when the target is reached, "I" attempts to drive the cumulative error to zero, resulting in an overshoot.
- **Derivative tuning:** attempts to minimize this overshoot by slowing the correction factor applied as the target is approached.

II.3.3.2 Types of PID Controller:

There are three basic types of controllers: on-off, proportional and PID. Depending upon the system to be controlled, the operator will be able to use one type or another to control the process

- on-off pid controller
- Proportional controls
- standard PID controller

II.3.3.3 PI formulation:

In order to have a digital PI controller in the system, one must first establish the discrete form of the PI controller.

The standard time expression of a PI regulator is as follows:

$$u(t) = K[\varepsilon(t) + \frac{1}{T_i} \int_0^t \varepsilon(\tau) d\tau] \quad (\text{II.28})$$

With, K: Proportional gain;

T_i: Integration constant.

From equation (II.28) calculate the numerical value of u (t) at t = nT, T is the sampling period.

$$u(nT) = K[\varepsilon(nT) + \frac{T}{T_i} \sum_{K=0}^{n-1} \varepsilon(KT)] \quad (\text{II.29})$$

Let us deduce the numerical value of u (t) at time: t = (n-1) T:

$$u((n-1)T) = K[\varepsilon((n-1)T) + \frac{T}{T_i} \sum_{K=0}^{n-2} \varepsilon(KT)] \quad (\text{II.30})$$

We subtract the two equations ((II.29) and (II.30)), we get:

$$u(nT) - u((n-1)T) = K \left[\varepsilon(nT) - \varepsilon((n-1)T) + \frac{T}{T_i} \varepsilon(nT) \right] = P_0 \varepsilon(nT) + P_1 \varepsilon((n-1)T) \quad (\text{II.31})$$

$$\text{Avec: } \begin{cases} P_0 = K(1 + \frac{T}{T_i}) \\ P_1 = -K \end{cases}$$

We do the Z transform of equation (II.18):

$$u(Z) - Z^{-1}u(Z) = P_0 \varepsilon(Z) + P_1 Z^{-1} \varepsilon(Z) \quad (\text{II.32})$$

Hence the discrete transfer function of the PI regulator:

$$\frac{u(Z)}{\varepsilon(Z)} = \frac{P_0 + Z^{-1}P_1}{1 - Z^{-1}} \quad (\text{II.33}) [23]$$

II.3.4 Pulse width modulation (PWM):

II.3.5 Principle:

Pulse-width modulation uses a rectangular pulse wave whose pulse width is modulated resulting in the variation of the average value of the waveform. If we consider a pulse waveform $f(t)$, with period T , low value y_{min} , a high value y_{max} and a duty cycle D (see figure 1), the average value of the waveform is given by:

As $f(t)$ is a pulse wave, its value is y_{max} , y_{min} for $0 < t < D.T$ and y_{min} for $D.T < t < T$. The above expression then becomes:

$$\begin{aligned} \bar{y} &= \frac{1}{T} \left(\int_0^{DT} y_{max} dt + \int_0^{DT}, y_{min} dt \right) \\ &= \frac{1}{T} (D.T.y_{max} + T(1-D)y_{min}) \\ &= D.y_{max} + (1-D)y_{min} \end{aligned} \quad (\text{II.34})$$

This latter expression can be fairly simplified in many cases where $y_{max} = 0$ as $\bar{y} = D.y_{max}$. From this, the average value of the signal \bar{y} is directly dependent on the duty cycle D .

The simplest way to generate a PWM signal is the intersective method, which requires only a sawtooth or a triangle waveform (easily generated using a simple oscillator) and a comparator. When the value of the reference signal (the red sine wave in figure 2) is more than the modulation waveform (blue), the PWM signal (magenta) is in the high state, otherwise it is in the low state.

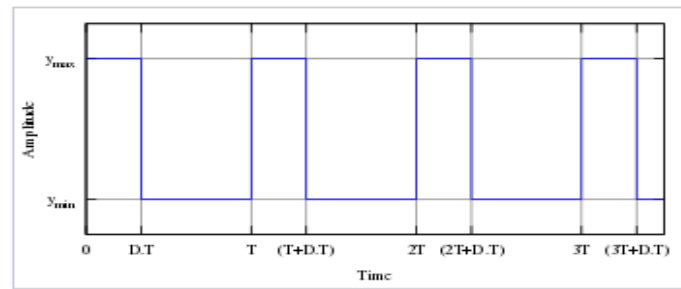


Figure 20: pulse wave . shwing the definition of y_{min} , y_{max} and D

II.4 Conclusion :

we have seen in this chapter ,the definition all the parts that make an emulator for a PEMFC (this characteristic /formulation) , in the next chapter we will collected all of them to modeling and simulate a PEMFC emulator.

Chapter III:

Simulation and results

The data provided by Avista Laboratories for the SR-12 stack was used to match the model proposed in this chapter. The procedure to obtain the parameters for this specific stack is as follows..[24]

- **Parameters of the SR-12 modular PEM generator:**

- **n**: number of FCs used in the stack;
 - **T**: membrane temperature used in the tests (K);
 - **A**: membrane active area (cm^2);
 - **ℓ** : membrane thickness (μm);
 - **P_{O_2}** : oxygen partial pressure (atm);
 - **P_{H_2}** : hydrogen partial pressure (atm);
 - **R_C** : membrane equivalent contact resistance (Ω);
- parametric coefficient, used in the calculation of the
- **B**: concentration losses (V);
 - **ξ_i** : ($i:1 \dots 4$): parametric coefficients, based on electrochemical, kinetics, and thermodynamic laws;
 - **Ψ** : parametric coefficient, used to model the membrane resistance (minimum 14, maximum 23);
 - **J_n** : current density representing the fuel crossover and
 - **J_{max}** : internal currents (A cm^{-2});

Parameters	Value	Parameters	Value
T	323 K	ξ_1	-0.948
A	62.5 cm^2	ξ_2	$0.00286 + 0.0002 \cdot \ln A + (4.3 \cdot 10^{-5}) \cdot \ln C_{H_2}$
N	42	ξ_3	$7.22 \cdot 10^{-5}$
P_{H_2}	1.47628 atm	ξ_4	$-1.0615 \cdot 10^{-4}$
P_{O_2}	0.2095 atm	Ψ	23
B	0.15 V	J_{max}	672 mA/cm^2
R_C	0.0003 Ω	J_n	22 mA/cm^2
L	25 μm	I_{max}	42 A

TABLE (III.1).the parameter of avista fuel cell model

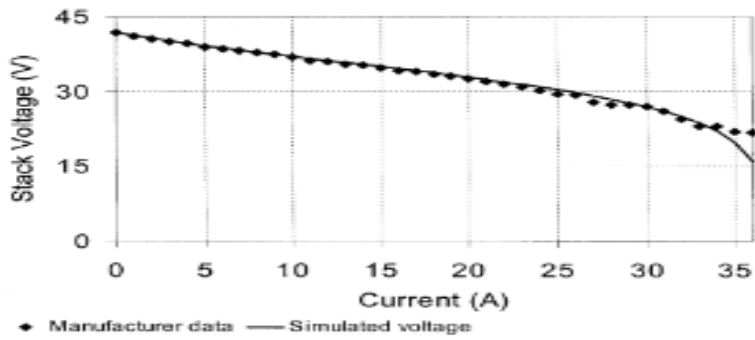


Figure III.2. Avista SR-12 PEM polarization curve.

III.3.1.1 simulation of PEM-FC model:

The PEMFC has been modeled, based on mathematical equation in chapter II the simulate is made under MATLAB/SIMULINK in order to analyze its performance. Fig. (III.3) shows the overall PEMFC model in MATLAB/Simulink

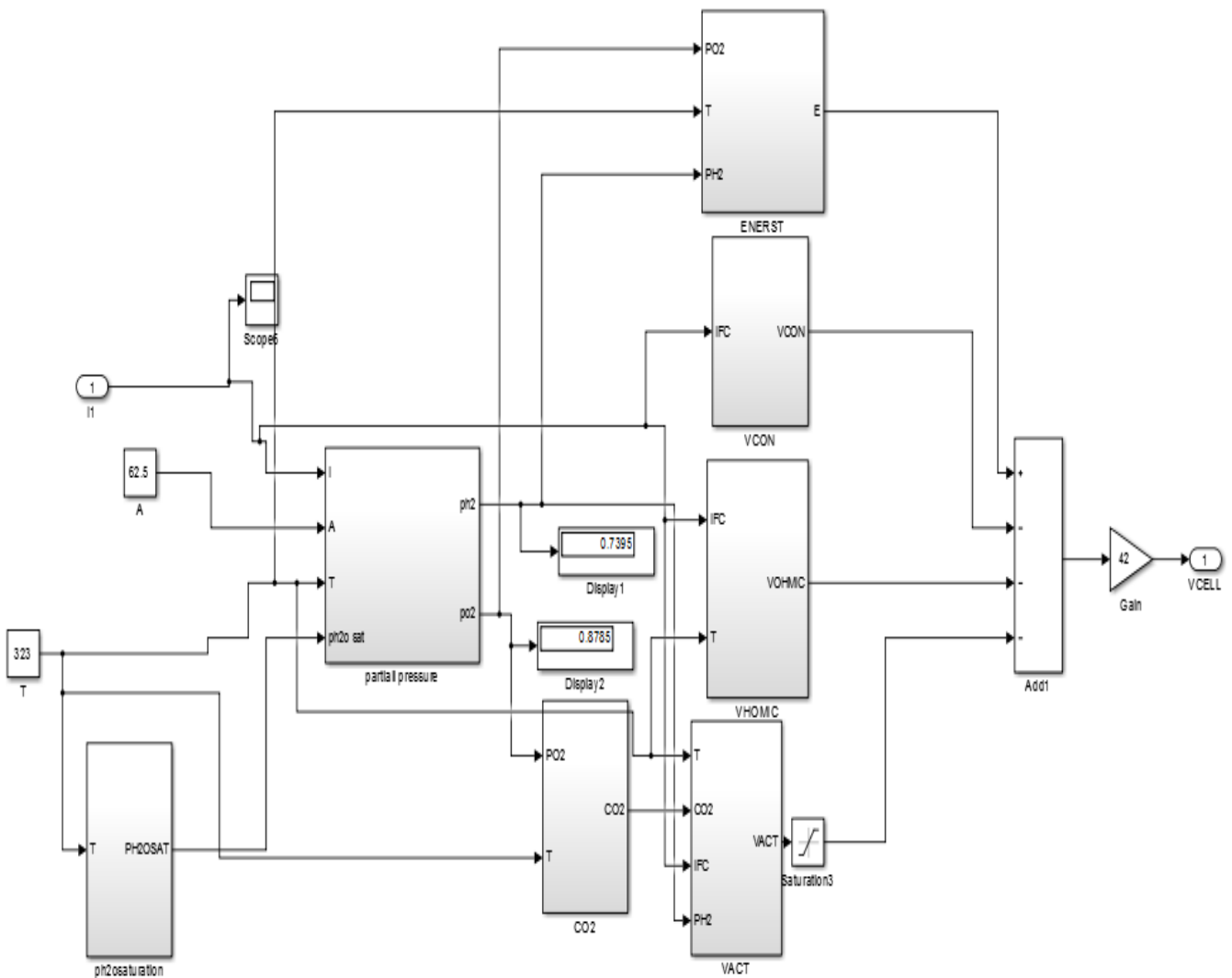


Figure III.3 . Overall mathematical model of fuel cell system

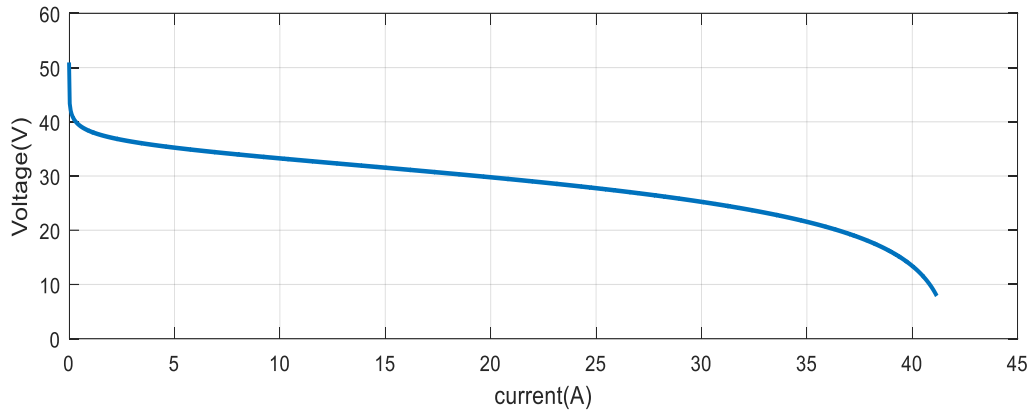


Figure III.4. polarization curve of studies PEM-FC model

We can see the polarization curve of studies PEM-FC model has the same polarization curve. Compared with experimental one figure (III.2), also through this curve we can improve our chosen PEM-FC model

III.3.1.2 Partial pressure of PEM –FC model:

Fig. (III.5) shows the saturation of water pressure model for the PEMFC. The calculation for the saturation water pressure can be explained by using the expression(II.3)(II.4).

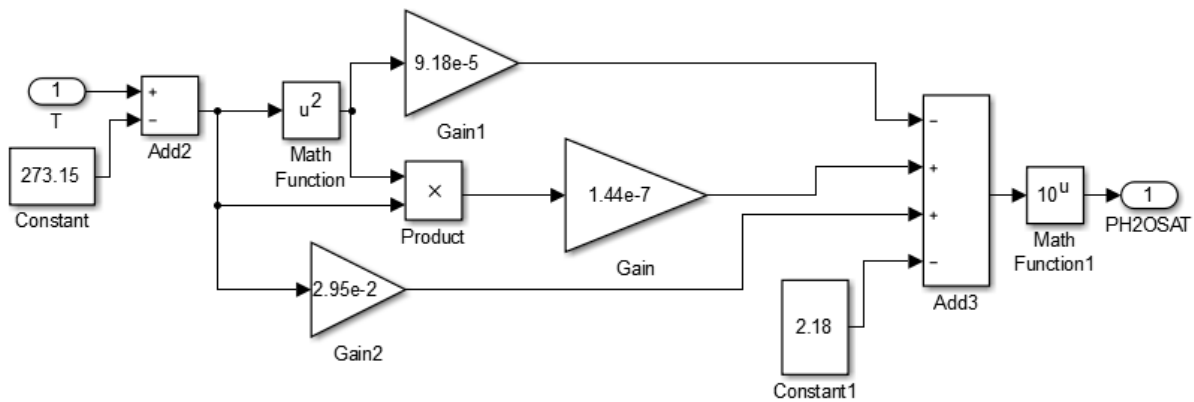


Figure III.5 . saturation pressure for water

Fig.(III.6) shows the partial pressure model of the PEMFC. The calculation of partial pressure can be explained based on equation (II.1) (II.2):

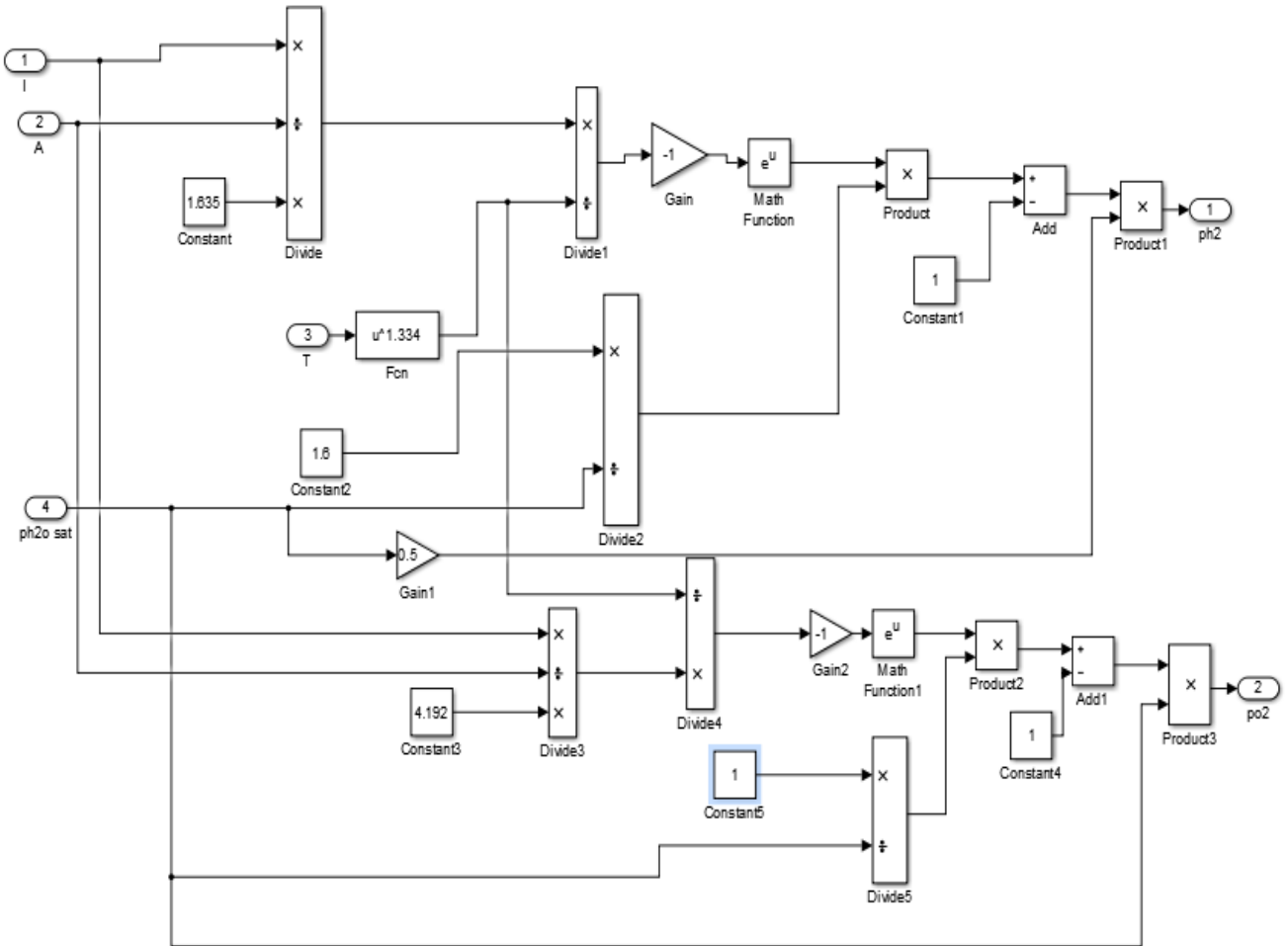


Figure III.6. Partial pressure of PEMFC

III.3.1.3 Cell Reversible Voltage:

Figure (III.7) shows The reversible voltage (E_{Nernst}) of PEMFC developed by using MATLAB/Simulink can be explained using the expression eq(II.5)

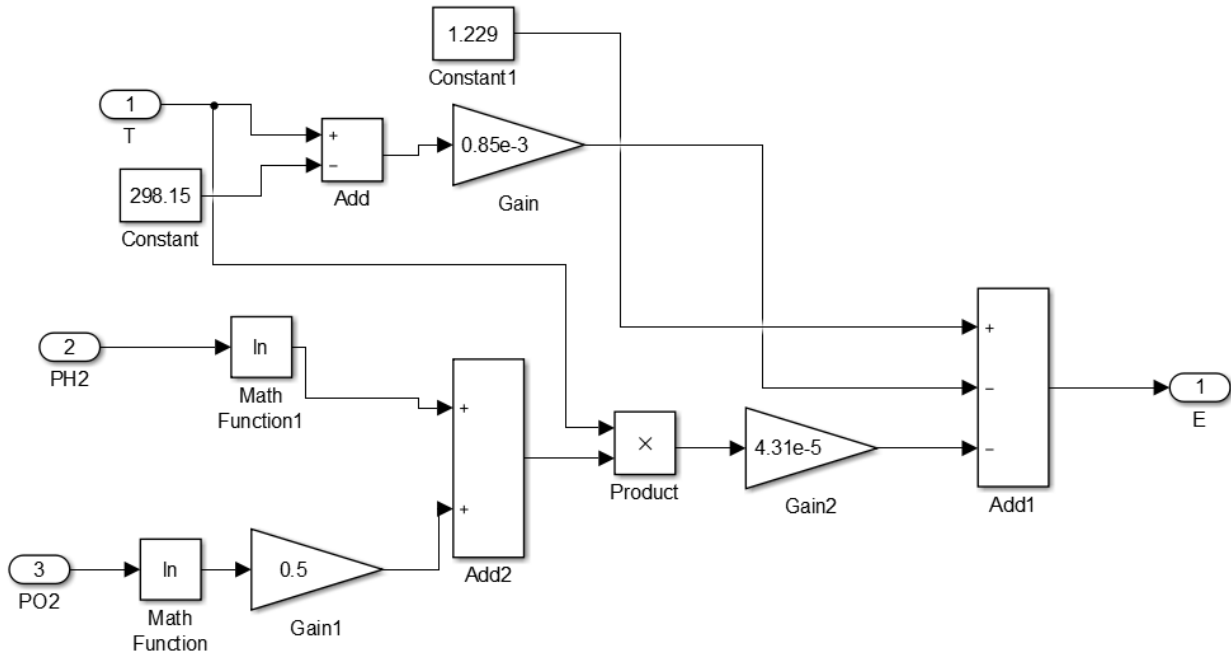


Figure III.7. The reversible voltage (E_{Nernst}) of PEMFC

III.3.1.4 Activation Voltage Drop:

Activation Voltage Drop model simulated under MATLAB/Simulink figure (III.8). and based on equation (II.7).

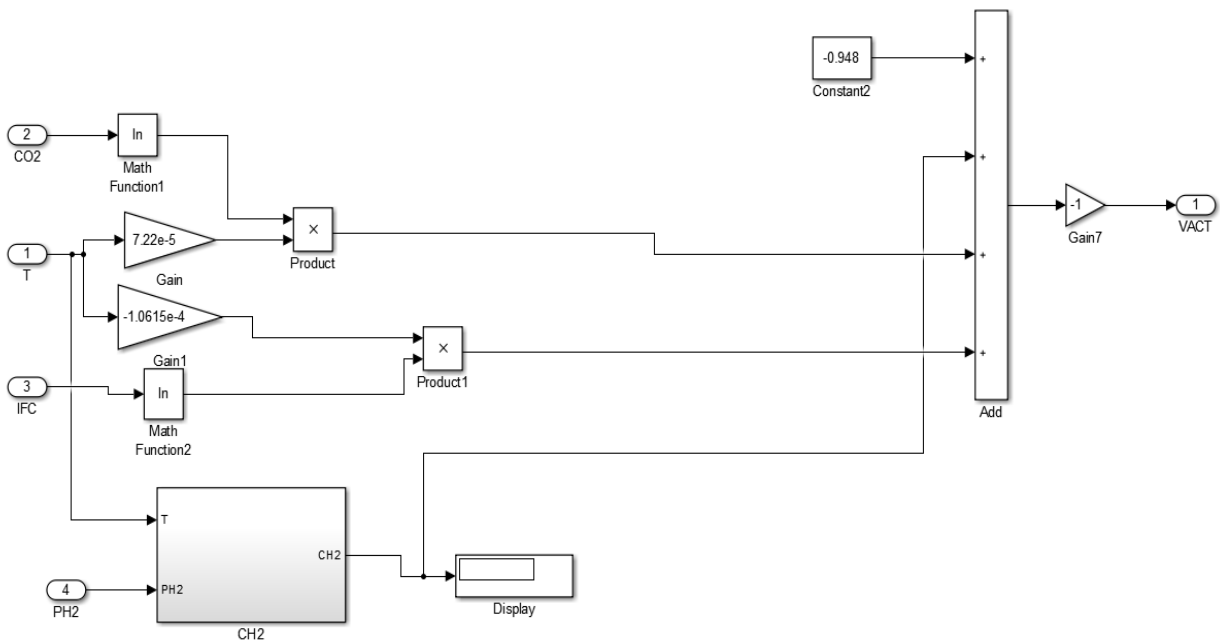


Figure III.8 . Activation Voltage Drop (V_{act}) of PEMFC

Present the concentration of hydrogen and oxygen, Simulated under MATLAB/Simulink environment , is shown in figure(III.9) and (III.10)

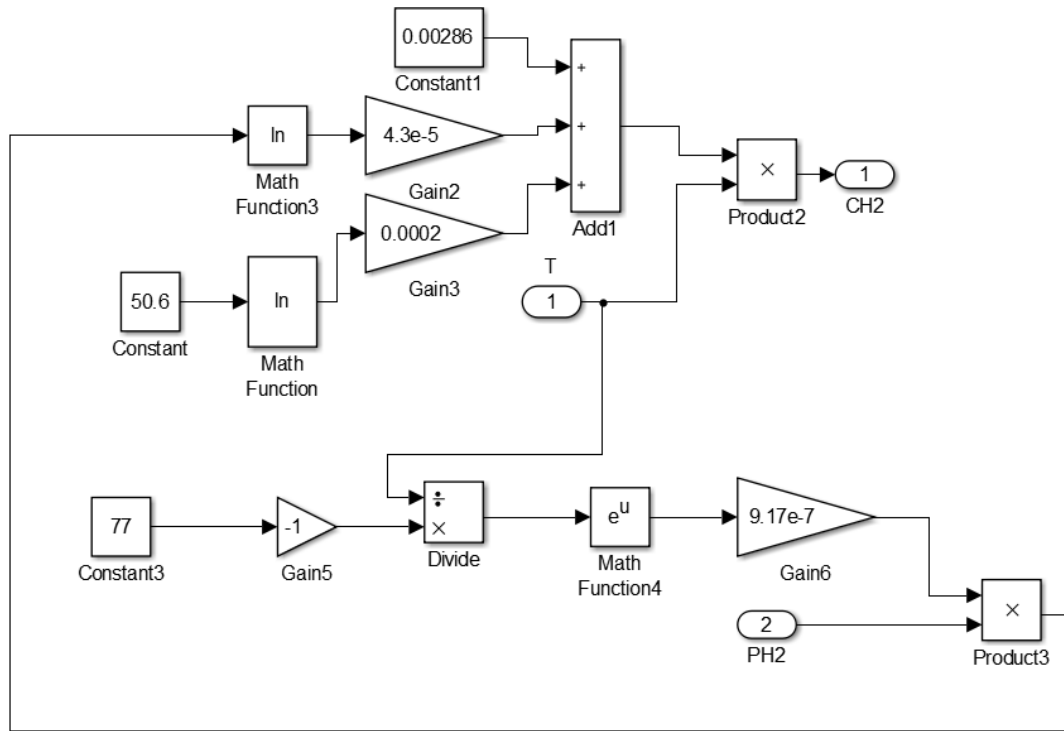
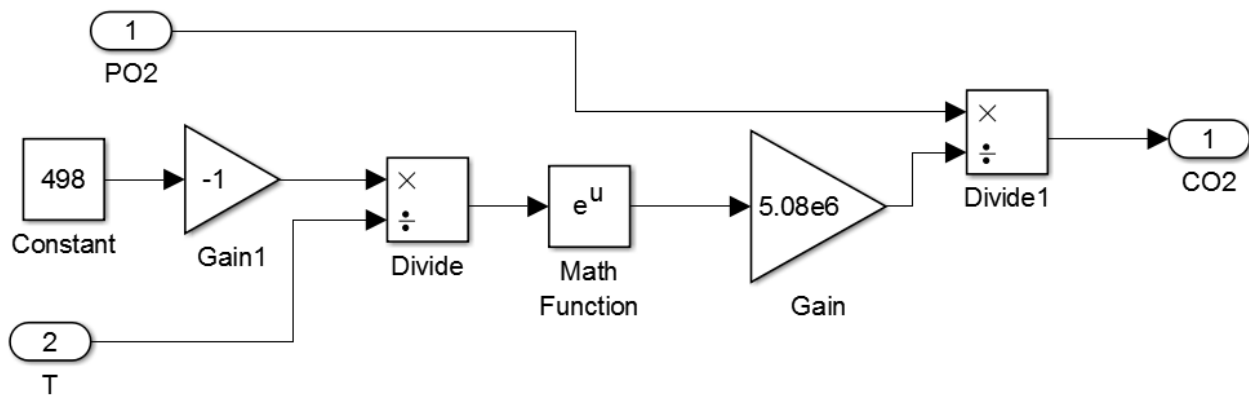


Figure (III.9). Model mathematical of C_{H_2}



Figure(III.10). Model mathematical of C_{O_2}

III.3.1.5 Ohmic Voltage Drop:

Ohmic Voltage Drop model developed by using MATLAB/Simulink are shown in figure (III.11). can be explained by using the expression(II.11)

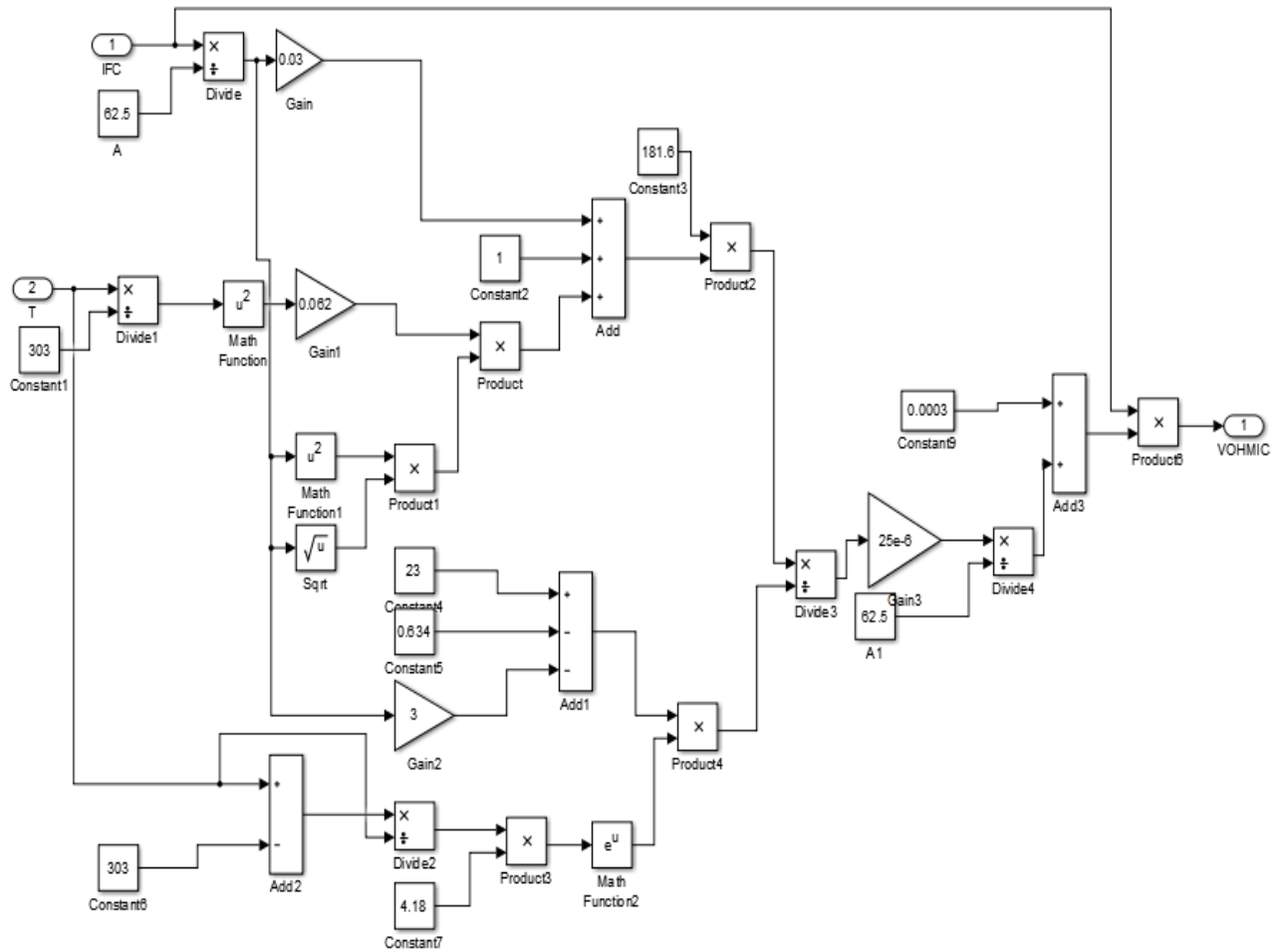


Figure (III.11). Ohmic Voltage Drop

III.3.1.6 Concentration Or Mass Transport Voltage Drop:

Figure (III.12) shows Concentration Or Mass Transport Voltage Drop simulated under MATLAB/Simulink and based on equation (II.13)(II.14).

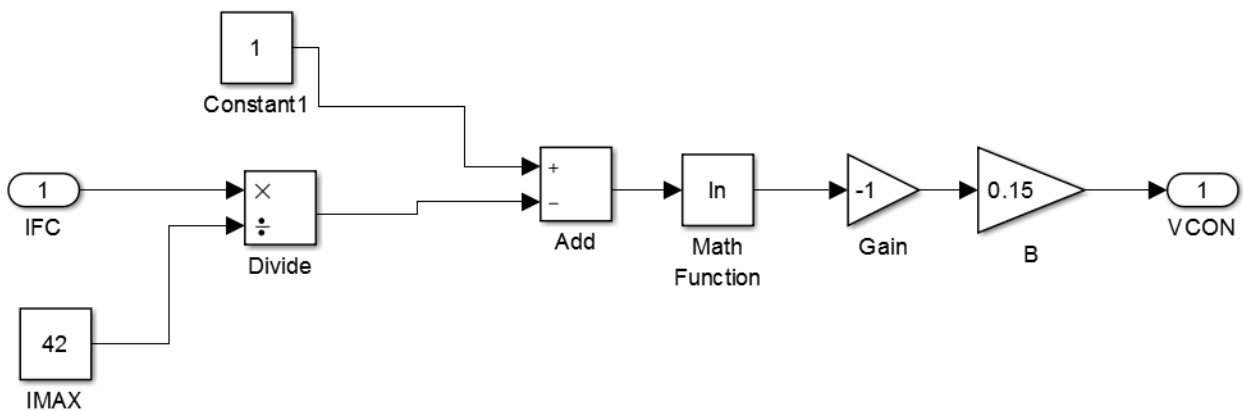


Figure (III.12). Concentration Or Mass Transport Voltage Drop

- The effect of oxygen on the polarization curve of PEM-FC model in order to show the effect of O_2 presser (PO_2) on the PEM-FC model , we try to take many values of PO_2 figure (III.14)

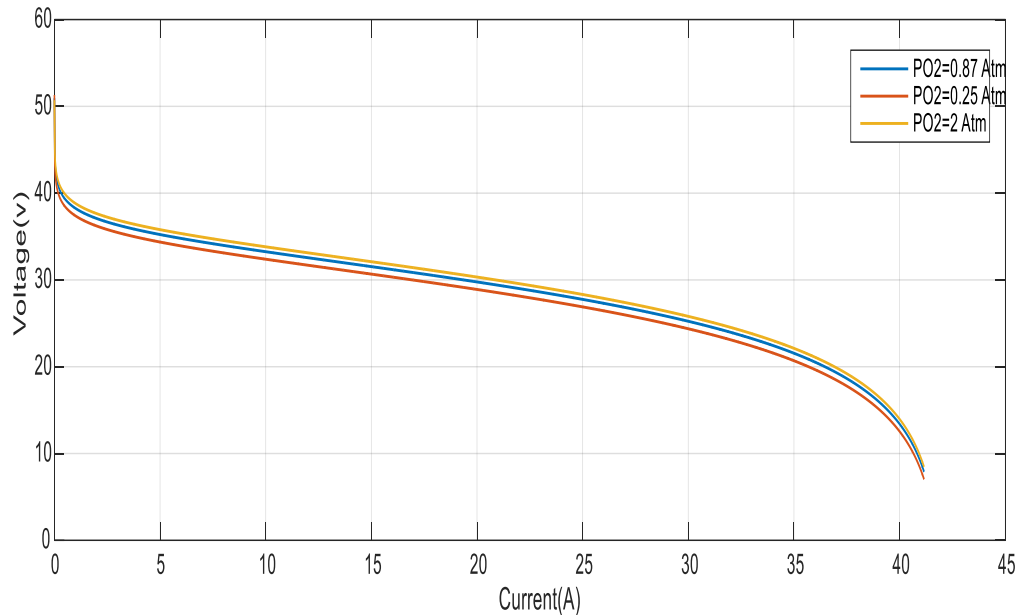


Figure (III.14). The effect of the oxygen on the voltage of PEMFC

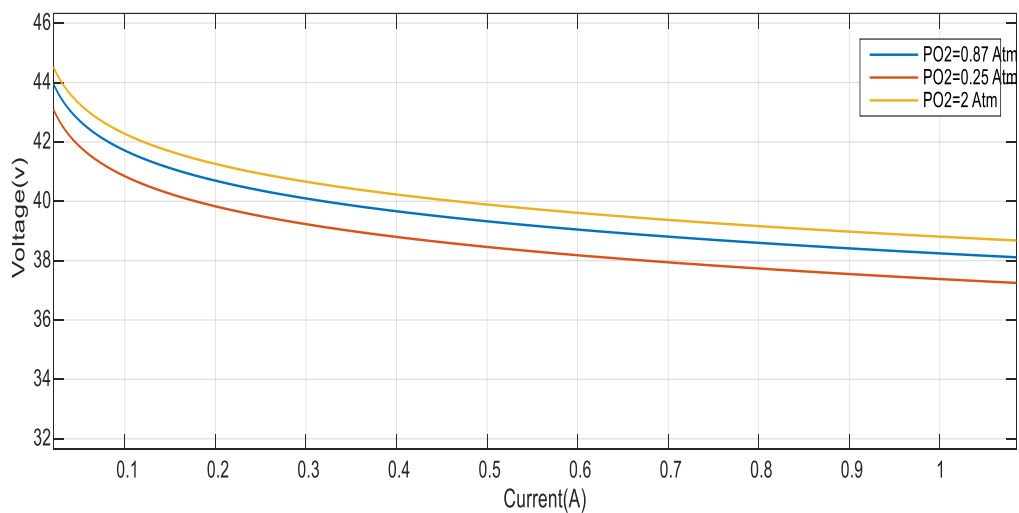


Figure (III.15).Zoom of the effect of the oxygen on the voltage of PEMFC

In figure (III.14) ,we can see the validation of our used (FC-PEMFC) through the variation of oxygen presser and we can see in this curves when the oxygen increase the generated power increase

III.3.2 The buck DC-DC converter :

A typical dc/dc buck converter is used to control the power of the fuel cell emulator, as shown in Fig(III.16).the simulation of this converter is made in MATLAB/SIMULINK

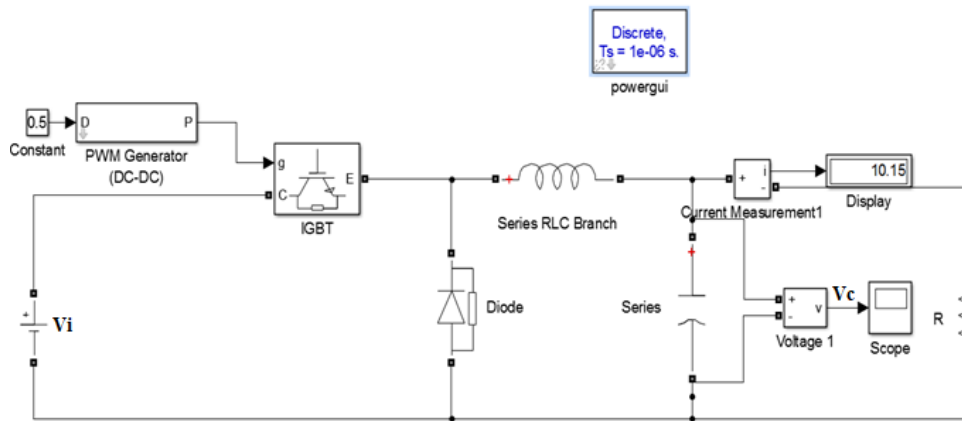


Figure (III.16).Step down DC-DC converter.

- Design of L and C DC-DC converter :

Converter Land C Conditioning

* Converter Inductance: The converter inductance value is calculated from the first condition which leads to the following design constraint :

$$L \geq \frac{T}{8 \cdot I_{min}} \cdot V_{in} = \frac{2 \cdot 10^{-4} \cdot 42}{8 \cdot 2} = 0.525 \text{mH} \tag{III.1}$$

The inductor value chosen for the simulation

$$L = 800 \mu\text{H}$$

* Converter Capacitance: The converter capacitance value should be chosen to meet the converter dynamic response needs.

With the fixed inductance value L (H) and the converter minimum cut off frequency f min (Hz), and the maximum value of the converter capacitance can be obtained :

$$C \leq \frac{V_{DCmax}}{8 \cdot L \cdot \Delta V_{max}} \cdot T^2 = \frac{41.7 \cdot (0.0002)^2}{8 \cdot (0.8) \cdot 10^{-3} \cdot (0.1)} = 2800 \mu\text{F} \tag{III.2}$$

On the basis of the design criteria in previous Equations, the LC filter components have been chosen with values as shown in Table III.2.

Model using the buck converter is described by two differential equations (III.1) and (III.2): the voltage at the terminals of the FC (V_c) and the current in the inductance (i_L) [26].

differential equation of DC-DC converter:

$$D = \alpha = \frac{t_{on}}{T} \quad (III.3)$$

Inductor current :

$$\frac{di_L}{dt} = \frac{1}{L} [(V_i - V_c) \alpha + (-V_c)(1 - \alpha)] \quad (III.4)$$

After the simplification:

$$\frac{di_L}{dt} = \frac{V_i}{L} \alpha - \frac{V_c}{L} \quad (III.5)$$

Capacitor voltage

$$\frac{dV_c}{dt} = \frac{1}{C} \left[\left(i_L - \frac{V_c}{R} \right) \alpha + \left(i_L - \frac{V_c}{R} \right) (1 - \alpha) \right] \quad (III.6)$$

After the simplification:

$$\frac{dV_c}{dt} = \frac{1}{C} (i_L) - \frac{V_c}{RC} \quad (III.7)$$

New variables :

$$i_L = x_1$$

$$\alpha = u$$

$$x_2 = y = V_c$$

And :

u : input

y : output

State equations:

$$\frac{dx_1}{dt} = \frac{V_i}{L} u - \frac{1}{L} x_2 \quad (III.8)$$

$$\frac{dx_2}{dt} = \frac{1}{C} x_1 - \frac{1}{RC} x_2 \quad (III.9)$$

Linearity

Homogeneity $f(0) = 0$ (III.10)

Superposition $f(a + b) = f(a) + f(b)$ (III.11)

By using “la place” method:

$$P(x_1) = \frac{V_i}{L} u(P) - \frac{1}{L} Y(P) \quad (\text{III.12})$$

$$P \cdot Y(P) = \frac{1}{C} x_1(P) - \frac{1}{RC} Y(P) \quad (\text{III.13})$$

$$C \cdot Y \left(P + \frac{1}{RC} \right) = x_1(P) \quad (\text{III.14})$$

By substituting in expression (III.12)

$$P \cdot Y(P) \cdot \left(P + \frac{1}{RC} \right) = \frac{V_i}{LC} u(P) - \frac{1}{LC} Y(P) \quad (\text{III.15})$$

$$Y \left(P^2 + \frac{1}{RC} P + \frac{1}{LC} \right) = \frac{V_i}{LC} u(P) \quad (\text{III.16})$$

$$\frac{Y(P)}{U(P)} = \frac{\frac{V_i}{LC}}{P^2 + \frac{1}{RC}P + \frac{1}{LC}} ; \frac{18750000}{P^2 + 1.5528 \cdot 10^3 P + 4.464 \cdot 10^5} \quad (\text{III.17})$$

Test of stability:

$$P^2 + 1.5528 \cdot 10^3 P + 4.464 \cdot 10^5$$

$$\Delta = b^2 - 4 \cdot a \cdot c = 6.2546 \cdot 10^5$$

$$P_1 = \frac{-b - \sqrt{\Delta}}{2 \cdot a} = -1.17 \cdot 10^3$$

$$P_2 = \frac{-b + \sqrt{\Delta}}{2 \cdot a} = -380.968$$

So the system stable.

LC filter		
Parameter	L	C
Value	800 μ H	2800 μ F

TABLE.(III.2): PARAMETERS OF LC FILTER

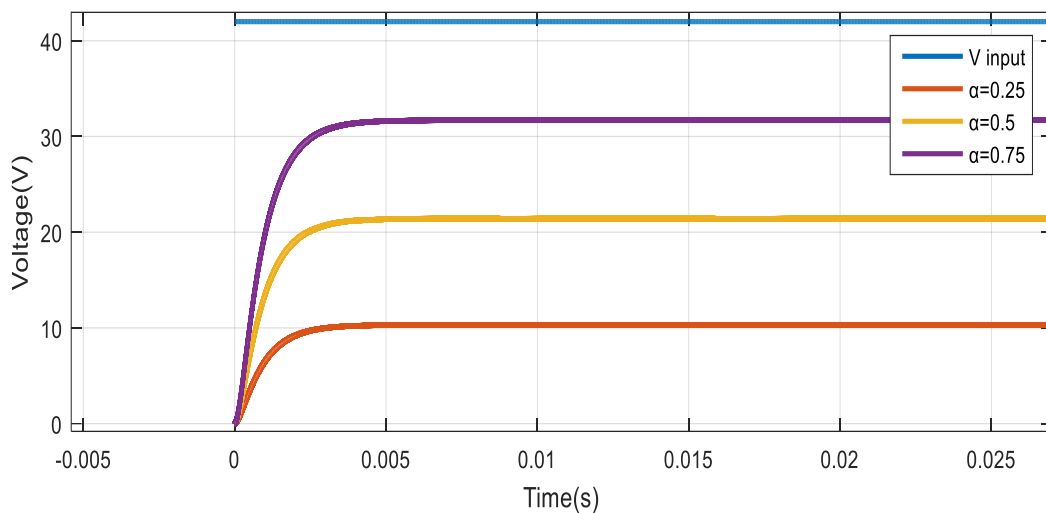


Figure (III.17): the DC-DC buck converter signal with duty cycle.

Through this figure we try to simulate the buck DC-DC converter under many values of duty cycle α , so our simulation achieved the equation

III.4 Emulator control:

The proposed control scheme in this work is based on a conventional PI controller in order to enhance and ensure the output voltage of the DC/DC buck converter to track the reference voltage that represent the fuel cell model voltage corresponding to the load current.

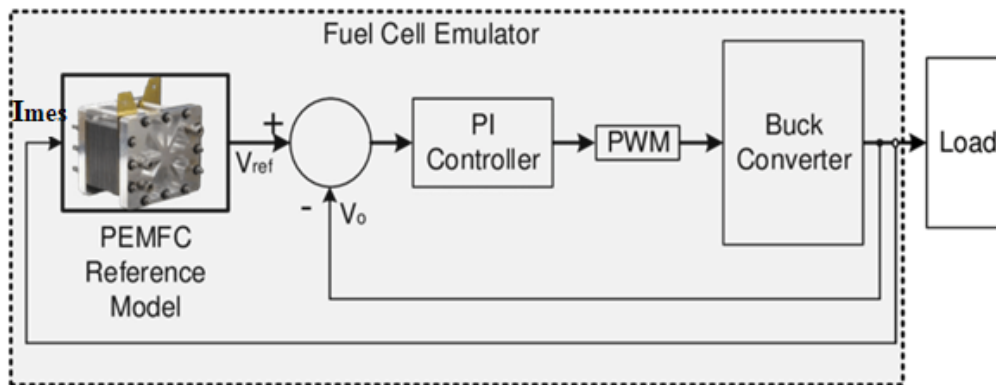


Figure. III.18: Emulator block diagram .

In figure (III.18) The error between the voltage reference (V_{ref}) and the measured output voltage V_o provided by the (L,C) filter is used by the PI controller to get the command signal that converted by PWM block to a duty cycle . To do this, we opted for a control (voltage) in terms of performance offered satisfactory and simplicity of implementation. These ones are proportional integrator regulators (PI), where the reference voltage V_{ref} is obtained from a mathematical model of PEM-FC.

We can see in the equation (III.17), the DC-DC converter has same a transfer function of second order for this purpose we try to synthesis the PI controller applied on that transfert function

Application of a proportional-integral regulator to a 2nd order system:

Let be a continuous process described by the transfer function of the form: $\frac{u(p)}{\varepsilon(p)} = \frac{K_0 \omega_0^2}{p^2 + 2\xi_0 \omega_0 p + \omega_0^2}$

The functional diagram of the control is shown schematically in the figure (III.19)

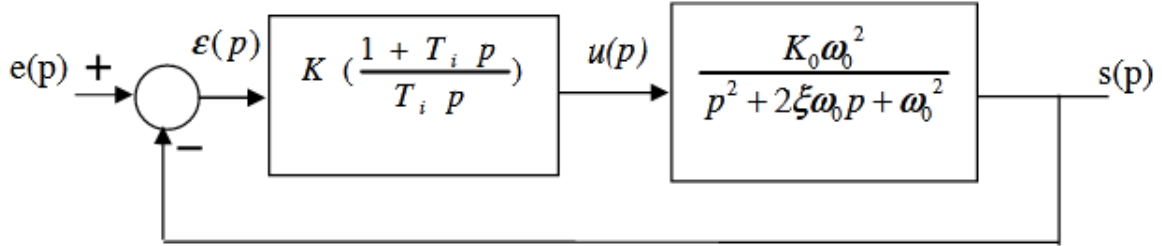


Figure (III.19): Control of a 2nd order system by a (PI)

The closed loop transfer function is expressed by:

$$\frac{S(P)}{E(P)} = \frac{\frac{KK_0(1+T_iP)}{T_iP} \frac{w_0^2}{p^2+2\xi_0w_0P+w_0^2}}{1 + \frac{KK_0(1+T_iP)}{T_iP} + \frac{w_0^2}{p^2+2\xi_0w_0P+w_0^2}} = \frac{\frac{KK_0w_0^2}{T_i}(1+T_iP)}{P^3 + 2\xi_0w_0P^2 + (w_0^2 + KK_0w_0^2)P + \frac{KK_0w_0^2}{T_i}} \quad (\text{III.18})$$

In closed loop, we notice that the system is third order. Its characteristic polynomial is written :

$$P^3 + 2\xi_0w_0P^2 + (w_0^2 + KK_0w_0^2)P + \frac{KK_0w_0^2}{T_i} = (P^2 + 2\xi_1w_{01}P + w_{01}^2)(P + P_0) \quad (\text{III.19})$$

First, we choose the second order behavior in closed loop by choosing (w_{01}, ξ_1) .

Secondly, we go to the resolution of these equations, to determine the parameters of the regulator (K, T_i) .

$$K = \frac{2\xi_1w_{01}P_0 + w_{01}^2 - w_0^2}{K_0w_0^2} \quad (\text{III.20})$$

$$P_0 = 2\xi_0w_0 - 2\xi_1w_{01} \quad (\text{III.21})$$

$$T_i = \frac{KK_0w_0^2}{P_0w_{01}^2} \quad (\text{III.22})$$

Compared with equation (III.13):

$$K = \frac{2\xi_1 w_{01} P_0 + w_{01}^2 - \frac{1}{LC}}{2V_i RC \sqrt{\frac{1}{LC}}} \tag{III.23}$$

$$P_0 = 2 \frac{1}{2RC \sqrt{\frac{1}{LC}}} \sqrt{\frac{1}{LC}} - 2\xi_1 w_{01} \tag{III.24}$$

$$T_i = \frac{KV_i \frac{1}{LC}}{P_0 w_{01}^2} \tag{III.25}$$

And ($P_0 > 0; K > 0$)

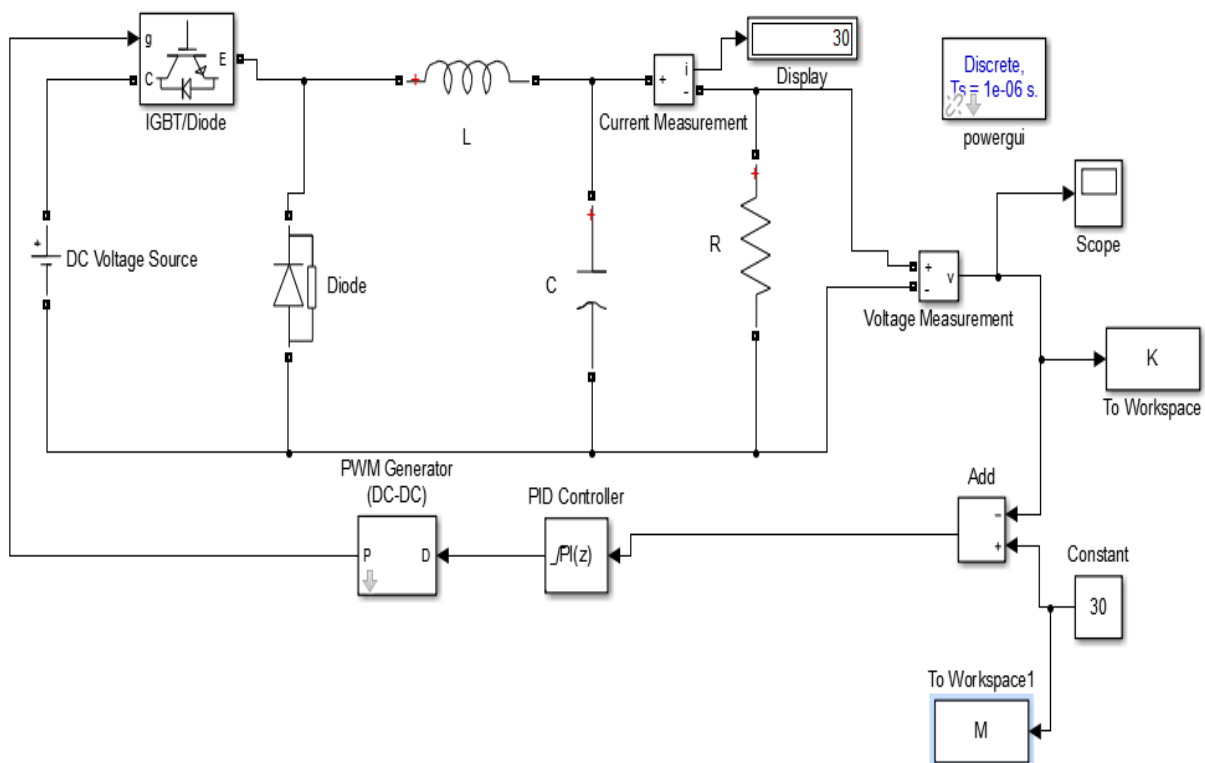
[25]

The proportional and integral gain of the PI controller values as shown in Table(III.2)

Parameters	Value
K	2.45
T_i	2.1

TABLE.(III.3).PI SIMULATION PARAMETERS

In order to test the values of K and T_i we designed a DC-DC converter with control PI using the MATLAB/simulink shawn in figure (III.20).



Figure(III.20): DC-DC converter without control PI test

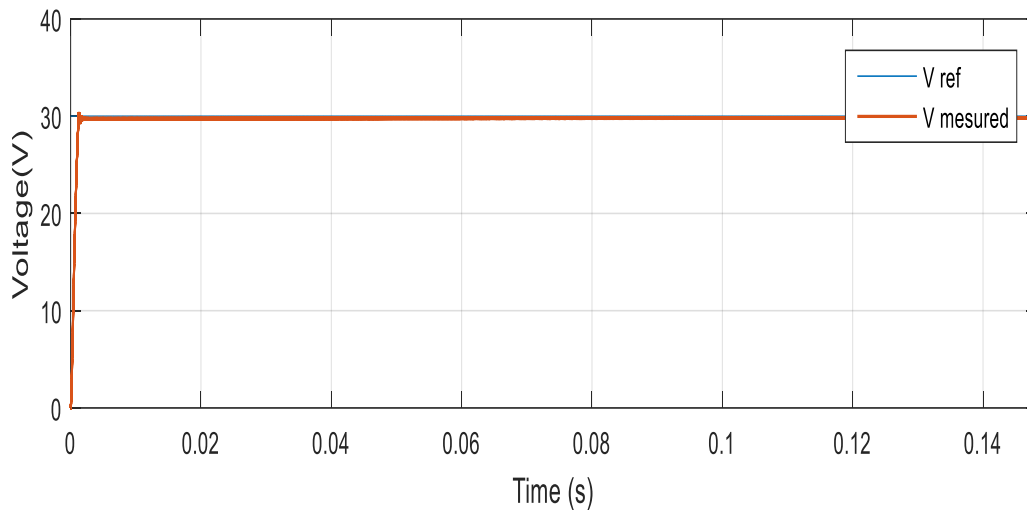


Figure (III.21): the output of the reference and measured Voltage

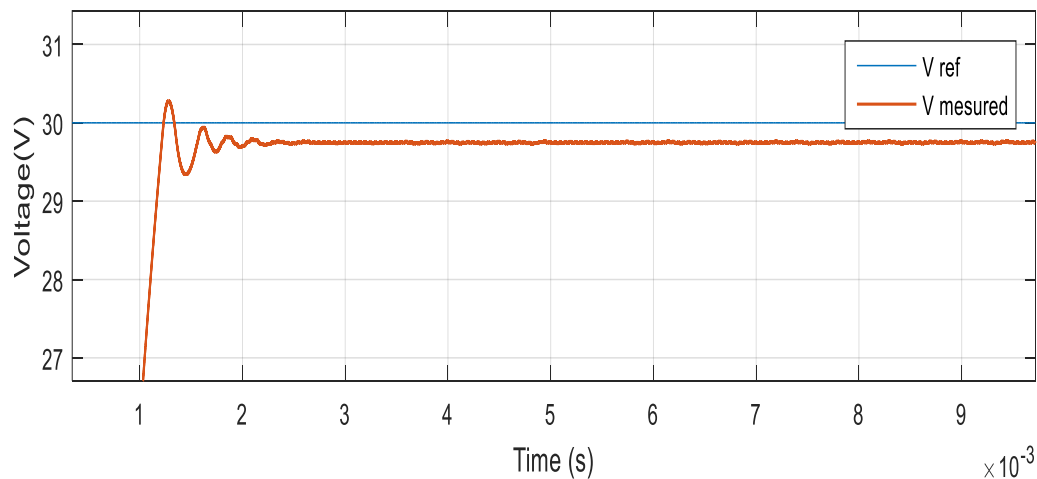


Figure (III.22): zoom of the output of the reference and measured Voltage

In this figure It can be concluded that the voltage measurement is very close and few errors in it with a difference in the reference voltage of 0.1 V and a quick response and in conclusion, we can say that the values of K and T_i are good.

III.5 Simulink and results:

In order to accomplish our FC-PEMFC based emulator a simulation whole system (FC model/DC-DC converter / PI controller) has been made on the Matlab/ Simulink environment, the choice of current scenario Fig (III.23) has been powered in order to test the performance of this emulator.

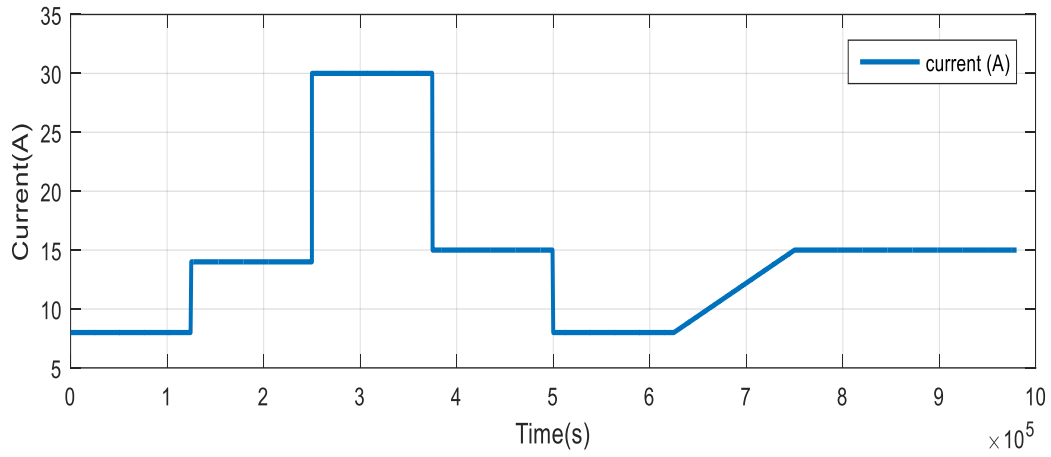


Figure (III.23): PEM fuel cell emulator output current

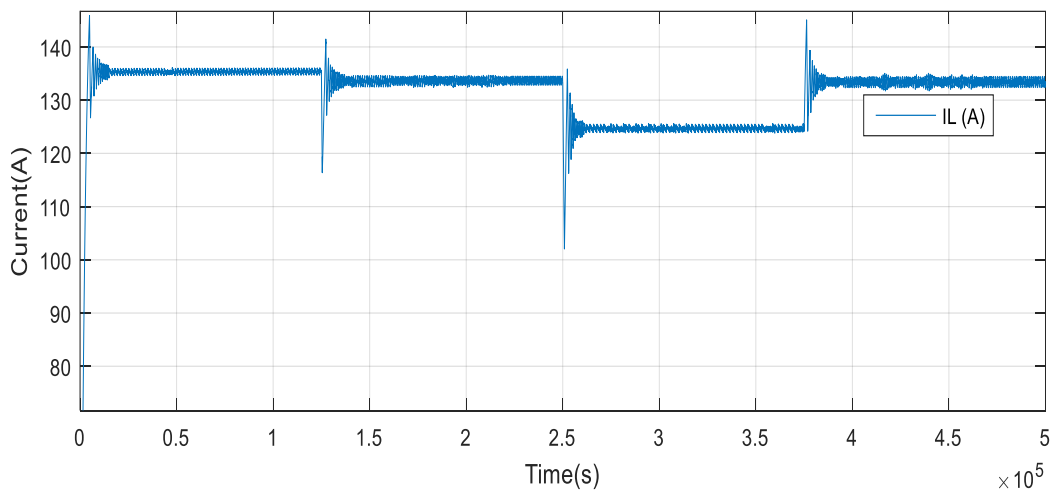


Figure (III.24):the scenario of inductor current

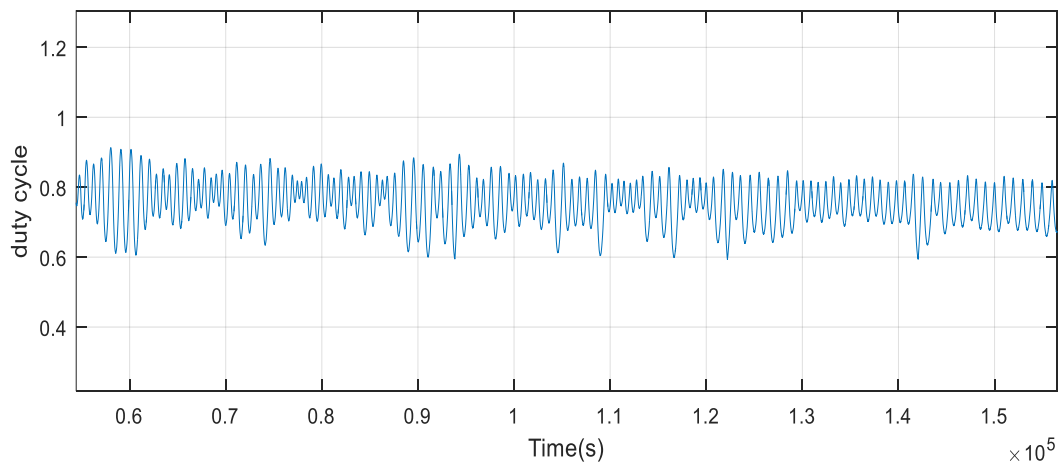


Figure (III.25): the rang of duty cycle that out from PI controller

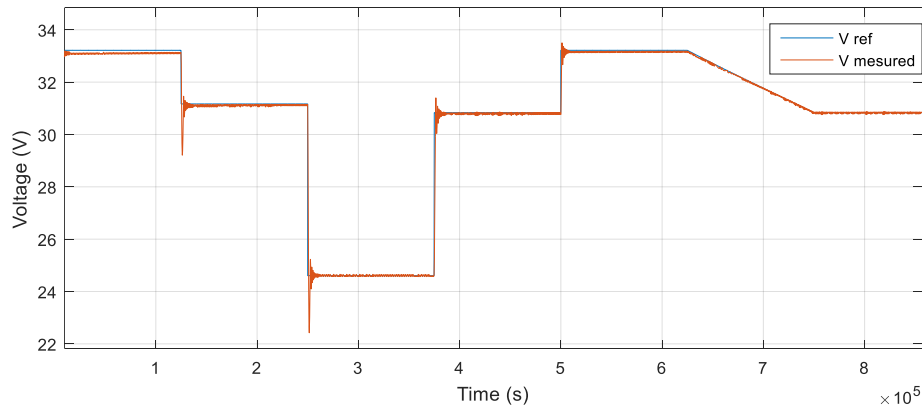


Figure (III.26): PEM fuel cell emulator output Voltage

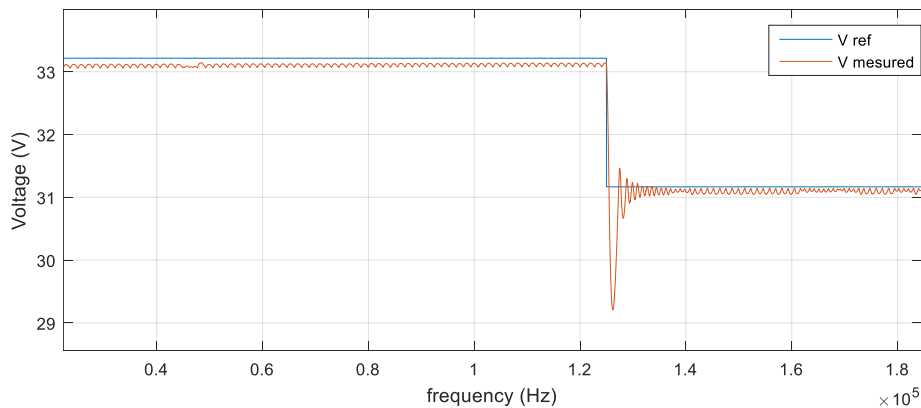


Figure (III.27): zoom on PEM fuel cell emulator output voltage

From the obtained results Fig (III.26), it can be concluded that the fitted model is very close to the emulator model. In conclusion, we can state that the parameterized mathematical model reproduce satisfactory the static and dynamic performances of the selected PEM fuel cell emulator. Also we saw how the PI controller generates good performance in point of view response time and robustness against abrupt change of current load.

III.6 Conclusion:

as a conclusion of this chapter , first of all can conclude , that our founded results are good in terms of validated model ,of FC-PEMFC ,DC-DC buck converter ,and calculated Vref-FC by PI controller ,the last one has proved by the respond time and rebustence against the variation of current load.

In this chapter, a PEMFC mathematical model is developed and simulated and an equivalent circuit model simulated. This validated SR-12 Modular PEM simulation simply requires a DC_DC buck converter for power electronics. It also appears when the oxygen pressure changes with the electrical voltage of the Vcell. Based on the simulation and instrumentation implementation of the fuel cell simulator, the requirements for high efficiency are met.

GENERAL CONCLUSION

General conclusion:

Now days a hardware emulators play very important role in many studies due its availability, flexibility, and extensibility.

Due to the international, electricity production strategy to reduce the C_{O_2} emission, many studies focus on the FC as a green energy .

Our Project based on the design, control and simulation of FC emulator, this project passed through many steps:

- The first one is the choice of type of the FC, and we based on the PEM-FC as studies type
- the second step is to modeled the chosen type (PEM-FC), In this step we focus on the DC-DC buck converter as a power part of FC emulator, This step reserved to the synthesis of PI controller, the role of this controller is to track the voltage reference of PEM-FC model
- The last step is to simulate the PEM-FC emulator under MATLAB/SIMULINK environment .

The obtained results proved and confirmed our choice of FC, DC-DC converter, and PI controller in point of view the tracking of FC behavior, response time, and robustness of system.

Also, through this project we have many benefits in our academic career.

As perspective we propose to the future promotion to pass in the experimental step in order validate experimentally our obtained results.

REFERENCES

- [1]: Fuel Cell Handbook, 5th Edition. Parsons Inc. October 2000.
- [2]: S. Gottesfeld, T. Zawodinski, Polymer electrolyte fuel cells, *Advances in Electrochemical Science and Engineering*. 5 (1997) 195-301.
- [3]: K. Sopian, and W.R. Wan Daud. Challenges and Future Developments in Proton Exchange Membrane Fuel Cells. *Renewable Energy* 31, 2006, 719-727.
- [4]: Pukrushpan, J.; Stefanopoulou A.G.; and Peng H.. Control of Fuel Cell Breathing, *IEEE Control Systems Magazine*, 2004. 30-46.
- [5]: "The Brits who bolstered the Moon landings". BBC. Retrieved 7 August 2019.
- [6]: "Apollo 11 mission 50 years on: The Cambridge scientist who helped put man on the moon". Cambridge Independent. Retrieved 7 August 2019.
- [7]: "The PureCell Model 400 – Product Overview". UTC Power. Archived from the original on 11 December 2011. Retrieved 22 December 2011.
- [8]: "S.Res.217 – A resolution designating October 8, 2015, as "National Hydrogen and Fuel Cell Day"". Congress.gov. 29 September 2015]
- [9]: Dicks, A. L., & Rand, D. A. J. (2018). *Fuel Cell Systems Explained*. doi:10.1002/9781118706992
- [10] : Dicks, A. L., & Rand, D. A. J. (2018). *Fuel Cell Systems Explained*. doi:10.1002/9781118706992
- [11]: Loyselle, Patricia; Prokopius, Kevin. "Teledyne Energy Systems, Inc., Proton Exchange Member (PEM) Fuel Cell Engineering Model Powerplant. Test Report: Initial Benchmark Tests in the Original Orientation". NASA. Glenn Research Center. hdl:2060/20110014968.
- [12]: Klippenstein, Matthew (24 April 2017). "Is Toyota's hydrogen fuel-cell fervor foolish, or foresighted? (with charts)". Retrieved 13 May 2017. Toyota's 2,000 or so Mirai sales in 2016 represented more than three times the megawattage of PEMFCs produced worldwide in 2014.
- [13]: Millington, Ben; Du, Shangfeng; Pollet, Bruno G. (2011). "The Effect of Materials on Proton Exchange Membrane Fuel Cell Electrode Performance". *Journal of Power Sources*. 196 (21): 9013–01*
- [14] : *Fuel Cell Systems Explained* Second Edition, James Larminie, Oxford Brookes University, UK, Andrew Dicks, University of Queensland, Australia; (Former Principal Scientist, BG Technology, UK)
- [15]: *PEM Fuel Cell Modeling and Simulation Using MATLAB®* Colleen Spiegel
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- [16] : COMPARATIVE STUDY ON DC-DC CONVERTERS BY :MEHEDI HASAN TUSHAR ID-09221205 p:7
- [17]: Schalenbach, Maximilian; Hoefner, Tobias; Paciok, Paul; Carmo, Marcelo; Lueke, Wiebke; Stolten, Detlef (2015-10-28). "Gas Permeation through Nafion. Part 1: Measurements". *The Journal of Physical Chemistry C*. 119 (45)
- [18]: Espinoza, Mayken (2015). "Compress effects on porosity, gas-phase tortuosity, and gas permeability in a simulated PEM gas diffusion layer"
- [19]: experimental investegatons of the wter impact on the performence of proton exgenge mempran
- [20]: Houari, A., Renaudineau, H., Martin, J.P., Pierfederici, S., Meibody-Tabar, F.: Flatness-based control of three-phase inverter with output LC filter. *IEEE Trans. Ind. Electron.* 59(7), 2890– 2897 (2012)
- Hung, J.Y., Gao, W., Hung, J.C.: Variable structure control: a survey. *IEEE Trans. Ind. Electron.* 40(1), 2–22 (1993)
- [21]: van der Hoeven, Jeffrey, Bram Lohman, and Remco Verdegem. "Emulation for Digital Preservation in Practice: The Results." *The International Journal of Digital Curation* 2.2 (2007): 123-132.
- [22]: Rothenberg, Jeffrey. "The Emulation Solution." *Avoiding Technological Quicksand: Finding a Viable Technical Foundation for Digital Preservation*. Washington, DC: Council on Library and Information Resources, 1998. Council on Library and Information Resources. 2008. 28 Mar. 2008
- [23]: cours asservissement, dr.boutoubat, amar thlidji university ,lagouat
- [24] :Correa, J. M., Farret, F. A., Canha, L. N., & Simoes, M. G. (2004). An Electrochemical-Based Fuel-Cell Model Suitable for Electrical Engineering Automation Approach. *IEEE Transactions on Industrial Electronics*, 51(5), 1103–1112. doi:10.1109/tie.2004.834972
- [25] :Azri, M., Khanipah, N. H. A., Mubin, A. N. A., Zukeri, M. Z. C., Ibrahim, Z., & Rahim, N. A. (2017). Development of PEMFC emulator using electrical equivalent circuit. 2017 6th International Conference on Electrical Engineering and Informatics (ICEEI). doi:10.1109/iceei.2017.8312363
- [26] Marsala, G., Pucci, M., Vitale, G., Cirrincione, M., and Miraoui, A. (2009). A prototype of a fuel cell PEM emulator based on a buck converter. *Applied Energy*, 86(10), 2192–2203. doi:10.1016/j.apenergy.2008.12.028