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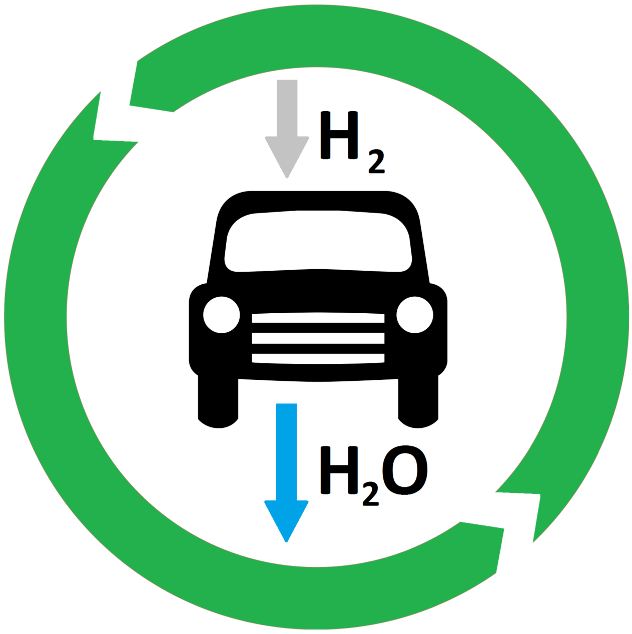

System Level modelling of fuel cell driven electric vehicles

Master's thesis in Electric Engineering

ALBERT CERDÁN CODINA

Elteknik Power Electronics Department
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Supervisor: Yujing Liu, Chalmers University of Technology
Examiner: Yujing Liu, Department of Energy and Environment Environment

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Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Basic illustration of the main principle of a fuel cell electric vehicle.

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ALBERT CERDÁN CODINA
Department of Energy and Environment
Chalmers University of Technology

Abstract

Nowadays, climate change is an issue of major concern for the majority of the world's society. Not just the emission of Greenhouse Gases but also the brutal pace at which fossil fuels are being consumed.

Within that topic and having innovation in mind, several alternatives have risen in the automotive industry in order to address this issue such as Battery Electric Vehicles or more recently at a commercial scale, Fuel Cell Vehicles. This last technology uses hydrogen as a fuel and transforms the chemical energy generated in the reaction with oxygen in electricity able to drive an electric motor, usually a PMSM.

This report will try to take an insight in this technology using different approaches. To do so, literature work will be done in order to review Hydrogen production, transportation and storage and how is now positioned as an energy resource in the world. Moreover, fuel cell technologies will be reviewed and explained as well as compared. Also, some literature work will be done in order to explain how a fuel cell vehicle operates and which are the most important elements of its drivetrain, also evaluating cost and feasibility of this kind of automotive solution.

Having reviewed the current state of the art of fuel cell technologies, this report will explain how the electric drivetrain of a fuel cell vehicle can be modelled in a Simulation platform such as MATLAB/Simulink. The most important elements of the fuel cell vehicle drivetrain will be modelled (Fuel cell stack, boost converter, power systems, etc.) and will be tested to see how they behave on its own and as a part of a small vehicle fuel cell drivetrain.

With the obtained results several conclusions were extracted as well as some future work pathways such as adapting the small scale model to a full power commercial vehicle model.

In all, this report will try to make clear how fuel cell vehicles can be considered as a feasible alternative to substitute conventional mobility methods.

Keywords: Fuel, cell, vehicle, hydrogen, Matlab/Simulink, electromobility.

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Albert Cerdán Codina, Göteborg, July 2017

Abbreviations

AC	Alternate current
AFC	Alkaline fuel cell
BEV	Battery electric vehicle
DC	Direct current
DMFC	Direct methanol fuel cell
FCV	Fuel cell vehicle
GDL	Gas Diffusion Layers
GHG	Greenhouse Gases
HPE	High Pressure Electrolysis
HV	High Voltage
IC	Internal combustion
MCFC	Molten carbonate fuel cell
MOSFET	MOS Field Effect Transistor
PAFC	Phosphoric acid fuel cell
PEC	Photoelectrochemical
PEMFC	Polymer electrolyte membrane fuel cell
PEM	Proton exchange membrane, Polymer electrolyte membrane
PFSA	Perfluorosulfonic acid, Nafion
PTFE	Polytetrafluoroethylene
PWM	Pulse Width Modulation
RFC	Reversible Fuel Cell
RFC	Reversible fuel cell
SOFC	Solid oxide fuel cell
STCH	Solar Thermochemical Hydrogen

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Introduction

1.1 Background

In the last few decades it has been demonstrated not only that global warming exists, but that if society continues to pollute and consume fossil fuels at this pace, will be irreversible. Moreover, it is clear enough to the major part of the society that the pace at which fossil fuels are being consumed is not sustainable enough and alternatives are needed in order to substitute petrol, coal and natural gas.

Nowadays there are many technologies that could actually partially or even totally substitute fossil fuels in energy matters, all related in some way to electricity production such as hydro power generation, wind power, photovoltaic, solar thermal energy, etc.

Just as energy industry, automotive industry which is always in a context of constant innovation has been inflicting change trying to find feasible alternatives to internal combustion engines which are the main cause of fossil fuel consumption and pollution in mobility currently.

During this last few years and in this context of constant innovation, several alternatives for internal combustion engines arose with the aim to find feasible options to fossil fuel consuming devices.

As one may recall, the main alternative for internal combustion cars is without a doubt BEVs (battery electric vehicle). Those vehicles rely on electricity in order to function, storing the electricity in a battery pack and using it to feed a motor in order to give motion. However, some issues are still to solve in order to make them as appealing as internal combustion cars. Two of the most important issues to tackle are mileage range and charging time.

On the other hand, fuel cell technology which began in the late sixties is beginning to take part in the automotive sector. Fuel cell technology converts chemical energy from a fuel into electricity through a chemical reaction by combining hydrogen from a continuous supply and oxygen from the air. As hydrogen makes its way through an electrolyte, electricity is generated. In the same way, hydrogen mixes with oxygen present in the air leaving nothing but water as a by-product of the process. Recently companies like Toyota, Hyundai, Honda or Nikola Motors have been making progress in this technology, and even launching commercial models sucha s the Toyota Mirai.

This type of technology takes advantage of hydrogen being the most abundant element in nature and tackles the problem of autonomy range and recharge time. On the other hand, nowadays hydrogen production is almost entirely accomplished by fossil fuel consumption.

1.2 Aim

This thesis has two different approaches. First, reviewing the various methods in which hydrogen is produced, transported and stored, as well as reviewing existing fuel cell technologies and how this technologies have been applied in the automotive sector.

Second and applying this knowledge, a Matlab/Simulink model of the electric system of a fuel cell vehicle will be implemented, taking in account all important parts of the system such as the PEMFC stack, the boost converter and the various power systems in order to see how a system of this kind behaves and how this elements interact with one another.

In order to achieve this aim several questions have been raised:

- How is hydrogen currently produced, transported and stored?
- Which are the current technologies regarding fuel cell and which of those have better properties and benefits regarding autowhen it comes to the automotive sector?
- How main fuel cell vehicle components operate and how they behave when working in synchrony?

1.3 Limitations

Regarding this thesis, limitations in perfecting a system and therefore a solution are mostly based in the delivery time. As time as an important limiting factor, only few tests will be evaluated and several hypothesis will be made regarding simulations in order deliver a complete result.

1.4 Methods

In order to review existing hydrogen, fuel cell and automotive industry fuel cell solution, literature work will be done.

Furthermore when model the elements of a fuel cell vehicle, MATLAB/Simulink platform will be done, obtaining system level models for all drivetrain elements for a fuel cell vehicle.

2

Hydrogen production, transportation and storage

2.1 Hydrogen production

As hydrogen doesn't typically exist by itself in nature, some processes have to be carried in order to obtain hydrogen as an energy carrier. Currently, most of hydrogen production comes from fossil fuel sources such as Natural Gas, Oil and Coal. The rest of hydrogen production is covered by alternative and renewable energy sources such as nuclear power, biomass, wind, geothermal, solar thermal, hydro-electric and solar photovoltaic power.

Current annual production is situated at 65 million metric tonnes of hydrogen, which is equivalent to approximately 8000PJ, a 2% of the world's total primary energy supply. If we divide hydrogen production by energy source, it can be seen that 48% comes from natural gas, 30% comes from oil refineries/chemical refineries, 18% from coal and only the remaining 4% from water electrolysis[1].

As seen, hydrogen can be obtained through a very wide range of processes. Here are listed and explained the most common and important ones:

2.1.1 Steam Reforming

Steam-methane reforming, or steam reforming is the most common method for hydrogen production throughout the world, representing over 3840PJ of the total produced hydrogen, and might be probably the most important technology pathway for a near-term hydrogen production, as this technology is far advanced and mature.

Steam reforming is an endothermic process (heat must be supplied in order for the reaction to take place) consisting in using a methane source such as natural gas and making it react with high temperature steam (roughly between 700°C and 1,000°C). The steam is put under 3 to 25 bar of pressure and all agents are in presence of a catalyst that helps the reaction take place. By-products of the reaction are hydrogen, carbon monoxide and carbon dioxide.

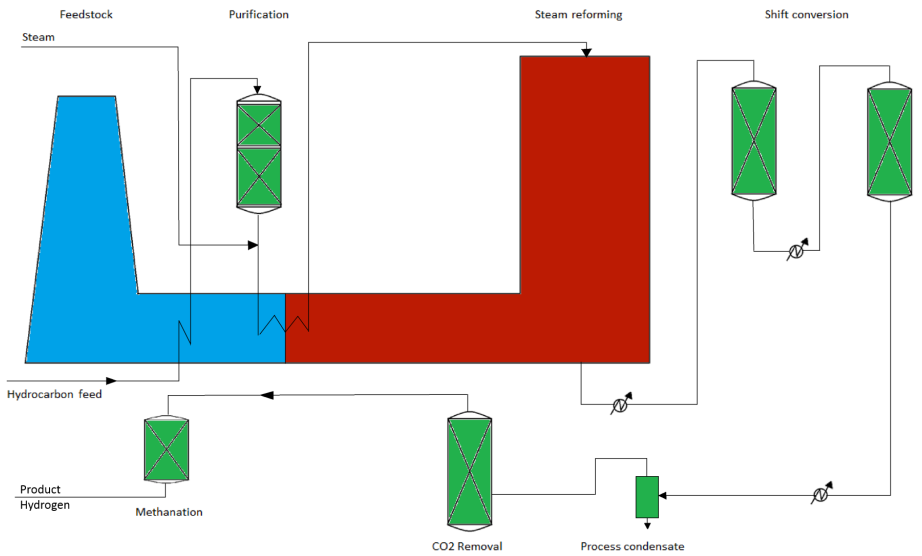


Figure 2.1: Steam reforming process

The chemical reaction for a high temperature steam reforming process would be the one listed below:

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \tag{2.1}$$

Once finished the first step of the process, carbon monoxide is submitted to another process in order to eliminate carbon monoxide and obtain carbon dioxide and more hydrogen. This process is called water-gas shift reaction, and the reaction would be as listed:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{2.2}$$

Note that for this second process the amount of heat that needs to be given is much less considerable than in the first process. In order to obtain pure hydrogen, the obtained mixture is put through a final step called pressure swing adsorption, which essentially removed carbon dioxide and by-products and waste to eventually leave pure hydrogen.

2.1.2 Gasification

The gasification process accepts multiple feedstocks such as coal, biomass, waste, petrol coke, or natural gas. Practically in the same way as the steam reforming process, coal, biomass etc. are put through a series of high temperatures and pressures along with oxygen and steam in order to obtain syngas (mainly carbon monoxide and hydrogen) and then, just as in the steam reforming process, the syngas is put through the water-gas shift reaction to obtain hydrogen and carbon dioxide.

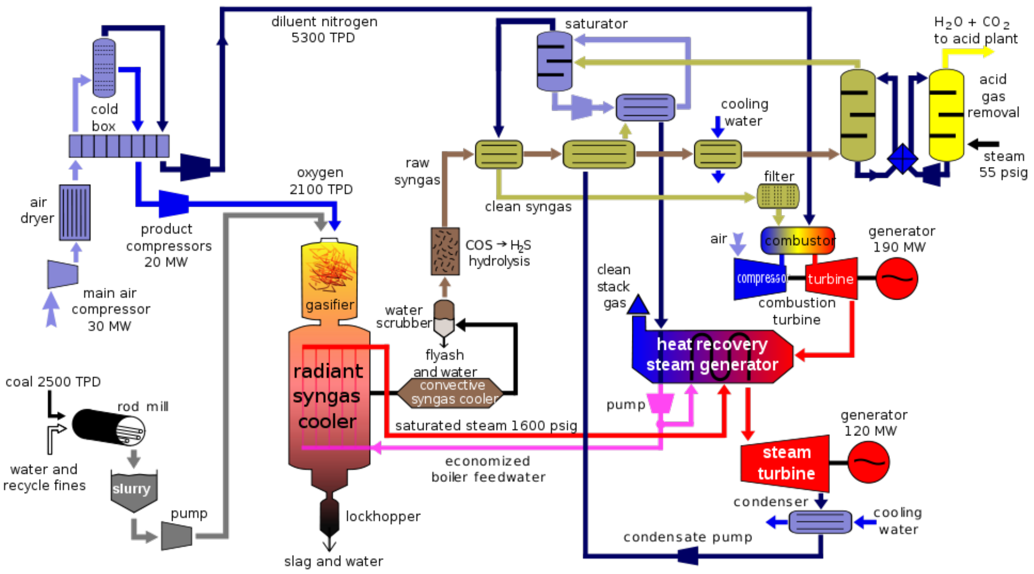


Figure 2.2: Gasification process [2]

Once more, when all processes are finished, hydrogen meeds to be separated from both carbon dioxide and other impurities in order to obtain pure useful Hydogen. Differently than in steam reforming, in gasification appear as well sulfur and slag as by-products, as seen in Figure 2.2.

Although these processes are not completely environmentally friendly as carbon dioxide is created, there are some existing solutions that help make hydrogen production a green process, such as carbon sequestration (process based on carbon dioxide capture so it is not released into the atmosphere). While it is true that it is not a vastly used technique, it helps making hydrogen production a clean process.

2.1.3 Partial Oxidation

Partial oxidation is a chemical process that takes advantage of the hydrocarbons in fossil fuels such as natural gas and oil. When oxidising a fuel, one can obtain water and carbon dioxide as by-products. However, if the amount of oxygen is not enough the chemical reaction obtained is a partial oxidation, where the obtained by-products are carbon monoxide and hydrogen.

Conventional combustion reaction:

$$\mathrm{C_nH_m} + \frac{2n+m}{4}\mathrm{O_2} \longrightarrow n\mathrm{CO} + \frac{m}{2}\mathrm{H_2O} \tag{2.3}$$

Partial oxidation chemical reaction:

$$\mathrm{C_nH_m} + \frac{n}{2}\mathrm{O_2} \longrightarrow n\mathrm{CO} + \frac{m}{2}\mathrm{H_2} \tag{2.4}$$

As seen in the chemical reactions (first one corresponding a natural combustion reaction, second one corresponding to partial oxidation reaction), one clear drawback would be that the amount of hydrogen produced per unit of fuel is less that in steam reforming or coal/biomass gasification. Nevertheless, partial oxidation processes do not require such big installations as in steam reforming processes and are much faster as well.

2.1.4 Water Splitting and Electrolysis

Watter splitting is the term used to refer to any kind of chemical reaction in which water is separated into oxygen and hydrogen. Achieving efficient and economical water splitting methods would be a key factor and breakthrough to hydrogen production, entailing green mass production of hydrogen and in that situation, making cars GHG emission free. Several water splitting techniques have been developed through time but currently only 4% of global hydrogen production is done following water splitting techniques.

Electrolysis is one kind of water splitting method which consists in breaking water molecules into oxygen and hydrogen, by applying an electrical current to it, as seen in Figure 2.3. Electrolysis requires a large quantity of electricity in order to produce high hydrogen quantities. For that reason, current methods such as steam reforming or gasification are much more used, as they require much less primary energy in order to produce the same quantity if hydrogen.

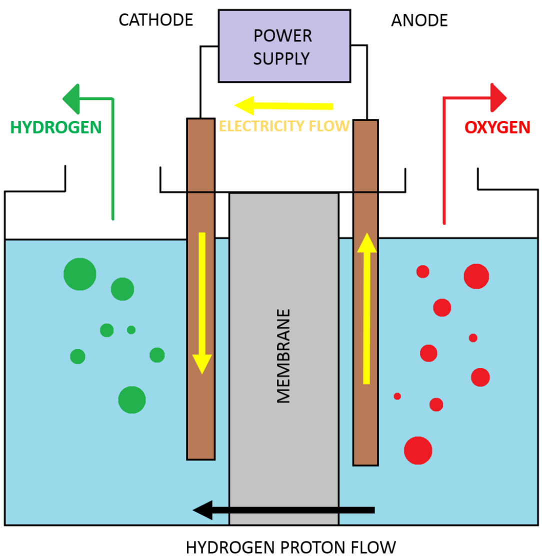


Figure 2.3: Electrolysis of water

However, electricity can be provided through renewable sources such as hydropower, solar photovoltaic, wind, etc. although this means that produced electricity is more valuable than the hydrogen produced, making this technique not feasible for economical benefits. A suitable candidate for electric production would also be nuclear power.

There are many different kinds of electrolysis and water splitting methods. Most used ones are listed and explained below.

2.1.4.1 High Pressure Electrolysis

High pressure electrolysis or HPE consists has the same mode of operation than a conventional water electrolysis. For a high pressure electrolysis water is split and hydrogen goes through a proton exchange membrane staying separated from the oxygen. The difference between those two processes is the hydrogen output. In a high pressure electrolysis, the hydrogen output is compressed around a pressure of 120 to 200 bar, which eliminates the need of an external compressor and therefore, total energy required per unit of produced hydrogen is less in a HPE than in a conventional electrolysis.

There also exist ultra high pressure electrolysis where the output hydrogen is at a pressure around 340 to 690 bar. For this process, modified proton exchange membrane are required in order not to affect hydrogen purity.

2.1.4.2 High Temperature Electrolysis

In high temperature electrolysis some of the energy required to obtain hydrogen is supplied in the form of heat rather than in electricity. This makes high temperature electrolysis more efficient than conventional electrolysis methods for two main reasons. First, electrolysis processes are more efficient at higher temperatures making it easier to break the bonds between water molecules. Second, as heat is cheaper than electricity, the overall process is more cost-efficient.

Average temperatures for high temperature electrolysis processes is normally between 100°C and 850°C. Considering that at higher temperatures efficiencies are as well higher, to obtain the same amount of hydrogen less thermal energy would be required at higher temperatures.

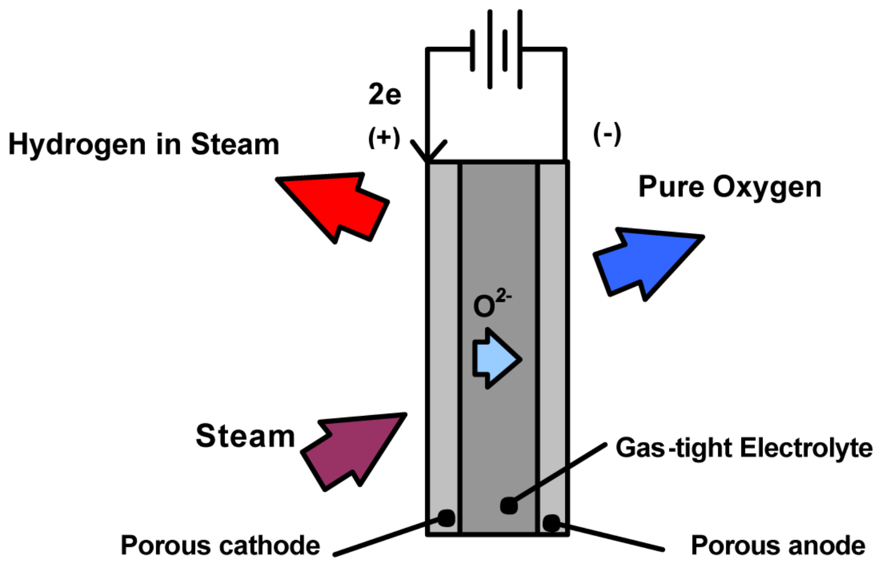


Figure 2.4: High temperature electrolysis [3]

2.1.4.3 Thermochemical Water Splitting

Thermochemical water splitting consists in taking advantage of solar power, concentrating solar radiation and therefore achieving temperatures between 500°C up to 2000°C. Although this is still a long-term technology option, it can achieve eventually no greenhouse gas emissions, which would make it one technological key factor in hydrogen production.

One main advantage of thermochemical water splitting is that all chemicals used along all processes are re-utilised. This creates a process that only consumes water and produces oxygen and hydrogen. However, in order to start the process, very high temperatures are required (as stated in the paragraph above). These temperatures can be reached following different methods:

- By concentrating sunlight into the receiver of a STCH reactor using a field of either plain heliostats or parabolic dish concentrators.
- Using waste heat from advanced nuclear reactors.

Nowadays several types of thermochemical water splitting cycles have been investigated and every one of them has its range of operating conditions and hydrogen production efficiencies. As said before, although being a long-term solution for hydrogen production, high production rates and efficiencies can be reached and at a certain point no greenhouse gases would be emitted, making this water splitting process a very feasible solution for granting hydrogen supplies to the market.

2.1.4.4 Photoelectrochemical Water Splitting

Photoelectrochemical (PEC) water splitting is a process that consists in producing hydrogen from water using both sunlight and photoelectrochemical materials (which are in fact specialized semiconductors). These materials use the energy form sunlight to split water molecules into hydrogen and oxygen.
In the same way that happens with thermochemical water splitting, PEC water splitting is a long-term solution for hydrogen production but it entails low or no greenhouse gases emissions to the atmosphere. Also, this processes can obtain the energy both from sunlight and nuclear energy processes.

2.2 Hydrogen transportation

There are currently several modes of hydrogen transportation divided into continuous (or pipeline), batch and ocean transportation. Choosing either one this transportation modes, it is crucial to have always pressurised vessels to transport hydrogen, which makes all transportation methods rather expensive. These different methods can be found explained in detail below.

2.2.1 Pipeline transportation

Gas and liquid hydrogen can be transported by pipeline. Taking this in mind, pipelines may vary in diameter, pressure, etc. Nevertheless, liquid hydrogen transportation by pipeline is mainly restricted to aerospace industry, where having liquid hydrogen is essential for the space shuttle. Otherwise, the amount of energy given to hydrogen just to keep it under cryogenic conditions is not feasible. For that reason industrial transportation of hydrogen occurs only with gaseous hydrogen.

Currently most pipeline systems are laid underground in order not to be affected by external events that may damage the infrastructure, and are made common material and then covered in anticorrosion coating in order not to be affected by embrittlement.

2.2.2 Batch transportation

Batch transportation for hydrogen is the most used method for transporting hydrogen, mainly because it needs to be stored in vessels or tanks to be transported. In that way it is easily transported while already stored. Vessels for batch transportation are filled either with compressed hydrogen or liquid hydrogen.

Any batch transportation process has three distinct processes:

- A refining process in order to remove impurities from hydrogen. Depending of the type of impurity that must be removed, different removal methods may be applied such as gas absorption or adsorption methods.
- A compression stage in order to fill the corresponding tanks/vessels. When filling the vessels hydrogen is usually compressed up to pressures around 15-30 MPa.
- Transportation of the vessels.

There also exists the possibility of ocean transportation in tankers, but currently liquid hydrogen tankers are not a widely accepted option to transport hydrogen due to the high amount of energy needed to keep liquid hydrogen in cryogenic conditions for the long period it requires.

2.3 Hydrogen storage

Hydrogen can be stored in many ways. However the most common ones are compressed hydrogen cryogenic hydrogen and liquid hydrogen storage. Find this storage modes explained below:

- Compressed hydrogen: Storage technique in which hydrogen is stored in tanks and pressurised. In the automotive industry, compressed hydrogen is kept at a pressure of either 350 bar or 700 bar, so tanks must be able to resist this high pressures without problem.
- Cryogenic hydrogen: This process consists in having hydrogen stored in tanks in liquid form, below hydrogen's critical point. Moreover, the cryogenic liquid is also compressed. While this method ensures great density per volume unit, it also entails a great amount of energy in order to keep the tank at cryogenic temperatures.

- Alternative storage techniques: While the two previous storage techniques are physical-based, recent investigations point towards material-based hydrogen storage. This means that using specific techniques such as absorption or adsorption, hydrogen molecules can be stored in certain materials, offering lighter solutions and with more power density than current used technologies. Nevertheless, this technology has to be considered in a mid to long term breakthrough.

3

Fuel Cells

3.1 Fuel cell mode of operation

Fuel cell are alike batteries, in the same way that they can be considered as a device capable of delivering sustained current and voltage when an energy input is given to them.

However, while a battery runs out of energy if not recharged, that is not the case for a fuel cell. A fuel cell will supply energy whenever is supplied with fuel without running down on energy. This energy comes in two forms: electric energy and heat.

A conventional fuel cell consists of two electrodes (anode and cathode) wrapped around and electrolyte. First, the fuel is supplied to the anode and a catalyst breaks the fuel into ions and electrons, which flow to the cathode generating electricity. At the same time air is supplied to the cathode, and oxygen molecules break and bond with hydrogen ions which have already gone through the membrane, forming water and heat as only by-products (see Figure 3.1).

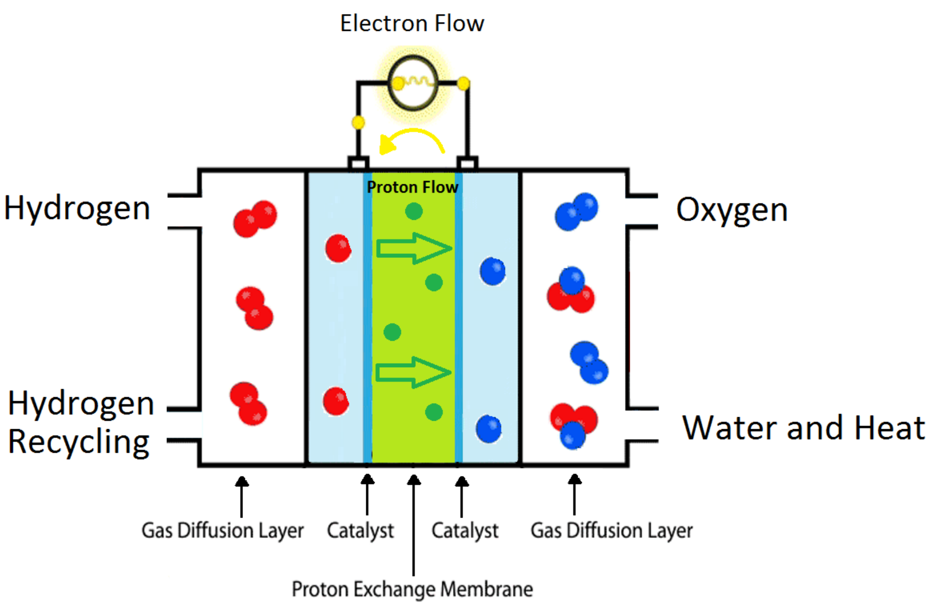


Figure 3.1: Proton exchange membrane fuel cell mode of operation

3.2 Parts of a fuel cell

Nowadays, most utilised and developed fuel cells for automotive applications are polymer electrolyte membrane fuel cells (PEM). PEM fuel cells are made from different materials, described below.

The main component of a PEM fuel cell is the membrane electrolyte assembly, which includes the membrane, the catalyst and gas diffusion layers.

To keep this structure all together, several annex components are used such as bipolar plates and gaskets. While bipolar plates are used to assemble each fuel cell into a bigger fuel cell stack in order to obtain the desired output power, the gaskets are used to seal the membrane electrolyte assembly and prevent in that way the possibility of gas leakage.

All this elements can be found described in more detail below.

3.2.1 Membrane electrode assembly

3.2.1.1 Polymer electrolyte membrane

The polymer electrolyte membrane (PEM) also called proton exchange membrane when working with hydrogen is a specialised device that only conducts positively charged particles through and blocks negatively charged particles. For that reason, when the catalyst breaks the hydrogen molecules into protons and electrons, protons go through the membrane and electrons go from anode to cathode generating electricity.

This semi permeable membrane is the main key component to fuel cell vehicles applications as it is the responsible from obtaining electric energy by not letting through electrons and other chemical substances that might cause the chemical reaction to stop or not to reach the desired efficiency level.

Proton exchange membranes can be from many different materials. Nowadays the most common material can either be pure polymer or composite membrane, where a material is wrapped around a polymer matrix. The most common material for membrane assembly nowadays is PFSA, a fluoropolymer also called Nafion. However, companies are starting to change the trend towards organic membranes, which are easier to recycle and entail less contamination while fabricating them. Average thickness for membranes in vehicle applications is under 20 μm. Also, recent research has proofed that membranes can be implemented at atomic level, thanks to graphene technology.

3.2.1.2 Catalyst layers

A catalyst is a chemical component that helps chemical reactions take place. In a fuel cell, the catalyst is placed between the membrane and both the anode and the cathode. Nowadays, conventional catalysts are made out of a very fine layer (nanometers of thickness) of platinum and dispersed in a carbon support, which is mixed with an ion-conducting polymer in order to let the ions flow through the membrane. The catalyst is normally put between the gas diffusion layers and the membrane. On the anode it helps the hydrogen split into protons and electrons and on the other side (cathode side) it helps the oxygen react with the protons enabling the formation of water.

3.2.1.3 Gas diffusion layers

The gas diffusion layers (GDLs) are the element which helps in the transport both hydrogen and the air stream into the catalyst and at the same time, helps the water to flow out of the fuel cell.

Gas diffusion layers are typically made of carbon coated with polytetrafluoroethylene (PTFE), a hydrophobic polymer that prevents water accumulation inside the fuel cell.

When gases incise in the gas diffusion layers, they rapidly flow through the pores of the carbon surface and then arrive to a microporous surface made of a coat of carbon with PTFE needed to maintain the balance between water expulsion and water retention, as some water is needed to maintain the fuel cell conductivity but too much reduces efficiency, as the pores in the gas diffusion layers need to be open in order to help the hydrogen and oxygen diffuse through the layers of the GDL and the membrane, for finally arriving to the electrodes.

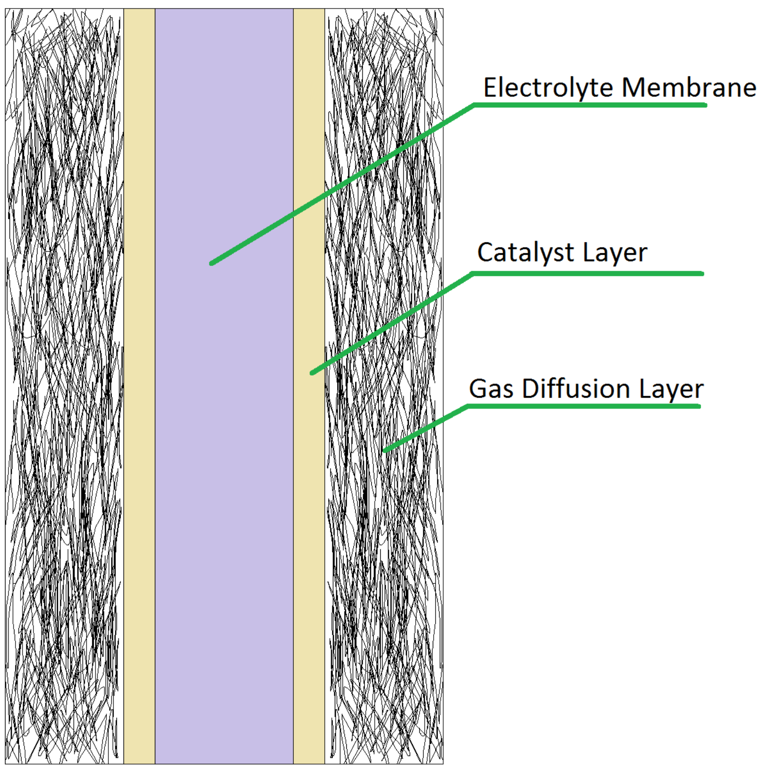


Figure 3.2: Parts of the membrane electrode assembly in a fuel cell

3.2.2 Gaskets

Gaskets are a vital part in the assembly of the membrane of a fuel cell. As a fuel cell is comprised between two plates that keep the membrane together, gaskets are added in order to make a gas seal. Gaskets are normally made out of elastomers (rubber polymers) so they can fit in the architecture of the fuel cell and gas doesn't leak.

3.2.3 Bipolar plates

As said before, the membrane of a fuel cell is built between two plates. This so called bipolar plates are put in the membrane fro two main reasons.

- First and foremost, a single conventional fuel cell produces in average less than 1V when submitted to typical operating conditions, and for automotive purposes more voltage is needed (average 400V to 600V). That makes necessary to create stacks of fuel cells, and these need to be separated from one another. This is possible thanks to the bipolar plates, which insulate each cell to develop its full functionality.
- Second and having in mind that most bipolar plates are fabricated in materials such as metal or composites (Glass fibre or carbon fibre), these elements not just bring the membrane altogether but also give stiffness and strength to the fuel cell and the fuel cell stack.

Those plates are usually machined following specialised patterns which try to get the gases in and out in the most aerodynamically efficient way through the fuel cell. To set as an example, in the new Toyota Mirai, bipolar plates have been designed concerning aerodynamics and flows of the intake and outtake gases and in that way efficiency has been augmented drastically. There also exist additional channels inside the plates for coolant circulation.

3.3 Types of a fuel cell

3.3.1 Polymer electrolyte membrane fuel cells

As said before, polymer electrolyte membrane fuel cells, also called proton exchange membrane fuel cells, are currently the most used type of fuel cell for most applications, including transportation and automotive industry applications. This type of cell is capable to deliver high power density (nowadays 0.7 $W \cdot cm^2$) as well as offering low weight and volume when put aside other types of fuel cells.

Once again, proton exchange membrane fuel cells use a polymer as an electrolyte, carbon electrodes and gas diffusion layers and platinum based catalysts. The main advantage of this type of fuel cell is that they feed from hydrogen and oxygen from the air.

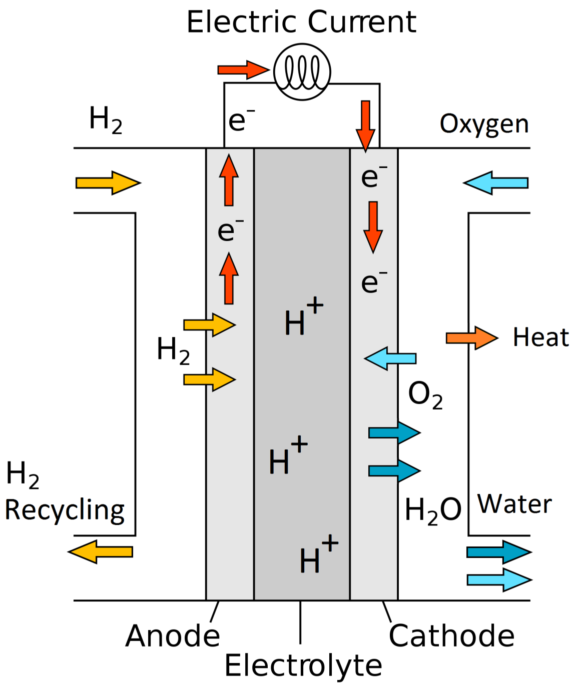


Figure 3.3: Drawing of a polymer exchange membrane fuel cell

Normal operating temperature for this type of fuel cell are around 80°C (considered relatively low temperatures). However, it has been proved that cold starts for fuel cell vehicles are possible even in below 0°C situations. As they are able to start in low temperatures, they have a quick start and that entail less wear of the components of the system and therefore, gives more durability to the whole set. Nevertheless, the use of platinum as catalyst increases the cost of the fuel cell stack drastically.

In all, PEMFC are a very suitable and feasible alternative for mass producing hydrogen powered vehicles due to how technologically advanced and reliable they are, as well as their good power to weight ratio.

3.3.2 Direct methanol fuel cells

Direct methanol fuel cells use pure methanol as fuel intake, which is usually mixed with water and fed directly into the fuel cell. As methanol has higher energy density than hydrogen, and has easier storage and transportation than hydrogen given that methanol is liquid as gasoline (current distribution network cold be useful). Normal operating temperatures for direct methanol fuel cells are between 60°C and 130°C, depending on the operation conditions and the electrolyte is normally a polymer.

Direct methanol fuel cells are used to power up portable systems such as laptops or mobile phones but also, this type of fuel cells has been starting to be utilised for military purposes due to its low noise and the non toxicity of the residue. Currently there are existing devices with powers between 25 watts and 5 kilowatts with durations up to 100 hours.

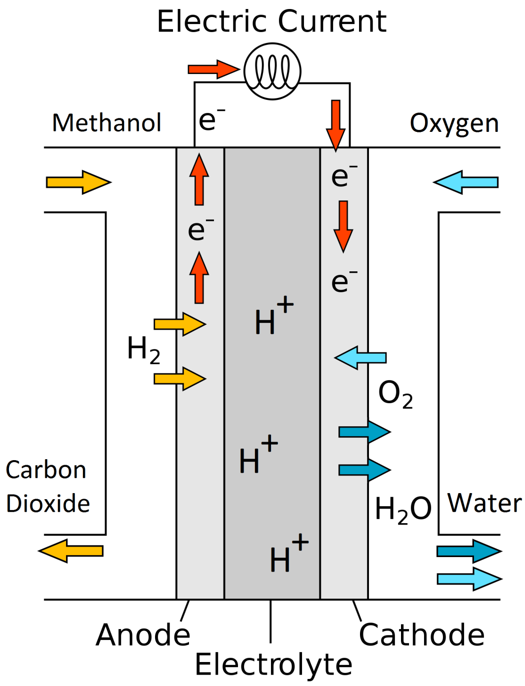


Figure 3.4: Drawing of a direct methanol fuel cell

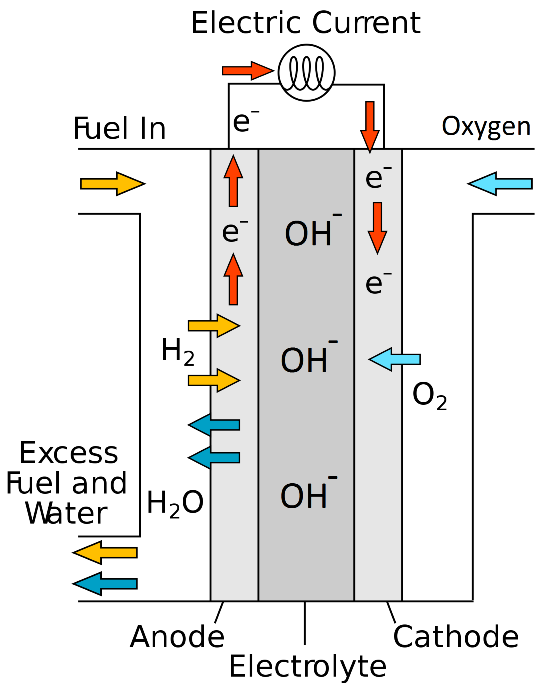
3.3.3 Alkaline fuel cells

Alkaline fuel cells were the first model to be developed and in fact, the most widely used in the U.S. space program in order to produce electricity and water on board of the spacecrafts.This type of fuel cell contains a solution of potassium hydroxide

that uses as electrolyte although in more recent models, electrolyte can be made of different kind of polymers as well. Alkaline fuel cells have been proved with efficiencies above 60%. This is in part due to the rate which electro-chemical reaction take place in the cell.

However, this type of cells has a main problem which is poisoning by carbon dioxide (CO_2). Having carbon dioxide poisoning can affect and decrease drastically the cell's durability and efficiency, as carbonate is formed and stuck in the key working components.

Nowadays, there exist two types of alkaline fuel cells; ones with a electrolyte solution (KOH) and others with a polymer alkaline solution. First ones carry several issues that affect global performance of the fuel cell such as high corrosion, pressure handling difficulties and humidity levels. Alkaline polymer membrane ones try to tackle this different issues and therefore, have a lower chance of CO_2 poisoning as well as better water management.



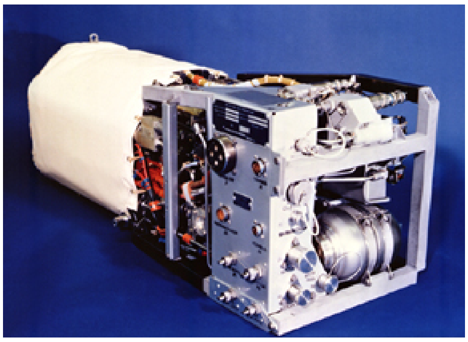


Figure 3.5: Drawing of an alkaline fuel cell's mode of operation and a NASA's alkaline fuel cell stack for aerospace purposes [4]

3.3.4 Phosphoric acid fuel cells

Phosphoric acid fuel cells (PAFCs) use a solution of phosphoric acid as electrolyte. The phosporic acid is contained in a Teflon and silicon carbide matrix and between carbon electrodes and platinum catalysts. The reactions that take place in this type of cell are the same as in a PEMFC, splitting hydrogen and bonding it to oxygen in order to produce water.

This type of fuel cell is considered to be one of the most mature fuel cell technologies, as it was the first to be used commercially. The uses for this type of fuel cell now are stationary power generation, but in some cases phosphoric acid fuel cells have been used for transportation purposes, implementing them in large vehicles such as trucks or metropolitan buses.

One advantage for phosphoric acid fuel cells is that they have more endurance in front of impurities in the hydrogen than proton exchange membrane fuel cells, as PEMFC have more easiness to bind carbon monoxide to the platinum catalyst in the anode, making the efficiency decrease.

In phosphoric acid fuel cells for stationary power generation, average efficiency is around 85% when used for co-generation of electricity and heat, and around 40% when solely used for electricity generation. These cells are typically large and heavy as they have a lower power per wheight ratio than other fuel cells and they are used for large energy amounts applications. In consequence, this type of cells are expensive as they need a large quantity of platinum to be fed into the catalyst.

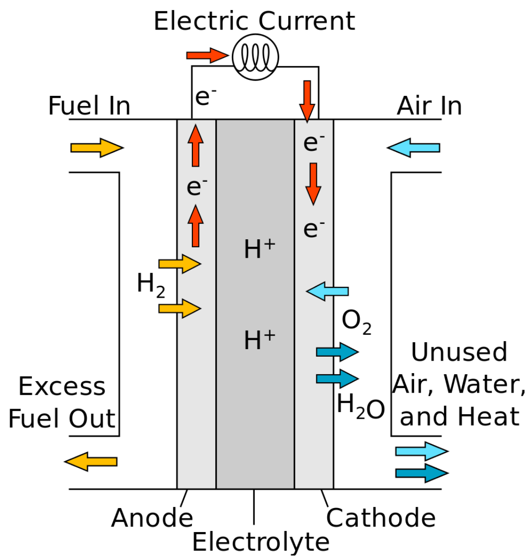


Figure 3.6: Drawing of a phosphoric acid fuel cell

3.3.5 Molten carbonate fuel cells

Molten carbonate fuel cells (MCFCs) use a molten carbonate mixture contained in a lithium aluminium oxide matrix. In order to keep the carbonate mixture molten, the cell has to work at very high temperatures of operation, which reduces the field of application for this type of fuel cells to industrial, power generation and milytary applications. However, as operating temperatures are around 650°C, many types of metals can be used as catalyst, reducing costs in manufacturing.

One major advantage of molten carbonate fuel cells in front of other types of fuel cells such as phosphoric acid fuel cells or proton exchange membrane fuel cells is that do not require an external fuel reformer, due to the high temperatures of operation. Fuels used in molten carbonate fuel cells are directly converted to hydrogen within the fuel cell (what is called internal reforming), which also reduces the overall cost.

Moreover, molten carbonate fuel cells also count with higher efficiency rates than phosphoric acid fuels. While phosphoric acid fuel cells have efficiency rates of roughly 40%, molten carbonate fuel cells can reach efficiencies up to 65% when assembled with a turbine. Also, when the residual heat of the process is used (co-generation), fuel cell efficiencies can reach up to 85%.

Nevertheless and despite the advantages commented right before, molten carbonate fuel cells have one major disadvantage, which is durability. Taking in account that operating temperatures are around 650°C and also that molten carbonate is corrosive, component breakdown and corrosion are quite common in this type of cell. Of course, corrosion and component breakdown cause durability of the fuel cell to decrease. Recent studies are focused in corrosion-resistant materials that can extend the fuel cell life up to approximately 5 years.

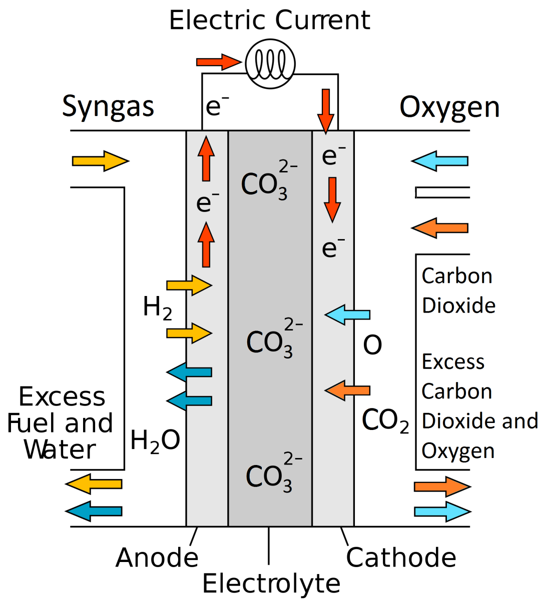


Figure 3.7: Drawing of a molten carbonate fuel cell

3.3.6 Solid oxide fuel cells

Solid oxide fuel cells (SOFC) use a solid oxide or non-porous ceramic compound as electrolyte. While in overall efficiency this cells have rates of approximately 60%, when applied in co-generation systems efficiency can climb up to 85% rates.

This type of fuel cell operates at very high temperatures (normally higher than 1000°C), which removes the need for the used of metals such as platinum as catalysts entailing a reduction of the overall cost of the fuel cell. Moreover, these temperatures allow the fuel to reform internally such as in the molten carbonate fuel cell.

Other advantages include for example low emissions, long-term stability and fuel flexibility. Solid oxide fuel cells are also the most sulfur-resistant fuel cell type. Additionally this type of fuel cell cannot be poisoned by carbon monoxide and can even be used as a fuel.

Nevertheless, having to work at high temperatures entails longer start-up times, it requires a significantly effective thermal shielding in order to maintain the heat of the process as well as protecting operators working alongside the fuel cell. As well as in molten carbonate fuel cells, durability is one of the main problems in solid oxide fuel cells, as working in such high temperatures affects the life of the cell components.

Is for that reason that new research lines are trying to tackle this issue in two different ways:

- By finding cost-effective materials that are resistant to corrosion at current operating temperatures.
- By developing a possible lower temperature solid oxide fuel cell (around 700°C), that would in fact have fewer durability problems. However nowadays lower temperature processes have not matched performance rates of high temperature ones and this technology is still under investigation.

Without doubt the research for new materials to work in a more efficient way in the cell will be the key component for a technological breakthrough in solid oxide fuel cells.

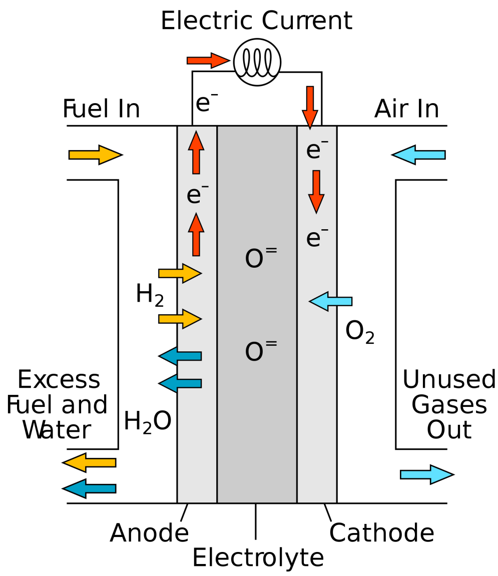


Figure 3.8: Drawing of a solid oxide fuel cell [5]

3.3.7 Reversible fuel cells

Reversible fuel cells (RFC) work the same way as conventional fuel cells, generating electricity and obtaining water and heat as by-products. However, reversible fuel cells can also take electricity from any source (may it be solar, hydroelectric, wind, etc.) and use it to convert water into hydrogen and oxygen using water splitting techniques.

In that way, this type of fuel cell can produce energy when needed but at the same time can use power peaks when other technologies produce in excess to produce and store hydrogen. That capability of producing energy but storing hydrogen (possible mass consume energy source in the future), could be a key factor in launching this kind of technology into the majority of the society. It could be a good energy system to implement in green households.

3.3.8 Fuel cell technology comparison

As seen in the paragraphs above fuel cells present several differences regarding temperature of operation or even fuel and electrolyte type. We can see below an explanatory table with all fuel cell types, operating temperature and type of fuel and electrolyte.

	Operating Temperature (°C)	**Fuel**	**Electrolyte**
PEMFC	40 - 90	H_2	Polymer
AFC	40 - 200	H_2	KOH
DMFC	60 - 130	Methanol	Polymer
PAFC	200	H_2	Phosphoric Acid
MCFC	650	H_2, CH_4, CO	Molten carbonate
SOFC	600 - 950	H_2, CH_4, CO	Solid Oxide

Table 3.1: Comparison of different fuel cell technologies

3.4 Fuel cell systems

3.4.1 Fuel processor

The fuel processor in fuel cell systems is the element responsible for converting the primary source of fuel into the usable form of fuel appropriate for every type of fuel cell. Depending on which type of fuel cell has the system, the fuel processor can be a simple filter to remove impurities or a more complex system with reactors and filters.

For systems using fuels such as methanol, gasified coal, gasoline or diesel, the conventional device widely used is a reformer, used to convert hydrocarbons into syngas (as explained in 2.1.1).

For other systems using fuels like molten carbonate or solid oxide, reforming can be done internally in the fuel cell taking advantage of the high temperature of operation of the fuel cell. This process is called internal reforming. However this process will still need filters to retain impurities before the reformed fuel reaches the fuel cell.

3.4.2 Power conditioners

Power conditioners are vital for controlling all parameters of an electrical current to meet the specifications of the system. These parameters include voltage, current, frequency, etc.

Fuel cells produce direct current and while many elements in the fuel cell system work with direct current, some other work with alternate current instead, as it is the case of the motor. For each cases, we need two different types of controllers or conditioners:

- On one hand and in order to work with DC currents, DC/DC converters are needed, usually boost converters to raise voltages between the battery and the inverter.
- On the other hand, to work with AC currents, it is usual to implement an inverter capable of transforming a certain DC current into an AC current stream with the desired amplitude and frequency. This is needed because one of the most important elements in the fuel cell system (as said before, the motor), works in the majority of cases with AC currents.

  Normally these converting and conditioning processes entail a reduction in efficiency as well, which goes between a 2% and a 6%.

3.4.3 Air compressors

As fuel cell overall performance is increased when pressure of the reactant increases as well, fuel systems include compressors which normally raise the pressure of the air intake up to 2 - 4 times the atmospheric pressure.

When it comes to transportation purposes, air compressors should have an efficiency of at least 75% and in some cases, an expander is also used to recover some power from the high pressure exhaust gases. The efficiency of the expander should be of at least 80%.

3.4.4 Humidifiers

As said before, polymer electrolyte membranes don't work well when completely dry but when kept at a certain humidity level. For that reason many fuel cell systems include humidifiers in order to raise the humidity of the inlet air to the fuel cell.

Normally, the humidifier is made from the same material as the polymer electrolyte membrane. This allows the system to obtain humidity from the produced water in the fuel cell and therefore keep the humidity in the fuel cell at the right level.

4

Fuel Cell Vehicles

Once explained how hydrogen is obtained and how energy can be obtained from it, we can proceed to take an insight of what fuel cell vehicles are and which are the key components of a fuel cell vehicle drivetrain.

Fuel cell technology started in the 19th century with the first primitive models of fuel cells but it wasn't until the year 1959 that fuel cells were implemented in a vehicle (a 15 kW fuel cell was implemented in an Allis-Chalmers tractor. Further on, the cold war and the space race between the US and the USSR brought fuel cell technology into deep investigation and development, with wide applications in aerospace technologies (as seen in 3.3.3 all fuel cells dedicated to aerospace technologies were alkaline fuel cells).

In 1966 general motors launched their first FCV, the Chevrolet Electrovan but only one unit was made, as the project was rejected for being cost-prohibitive. It wouldn't be until the late 90s that most car companies would start developing their own FCV models.

Nowadays there exist several companies that have placed a strong bet on fuel cell vehicles. The most important ones with cars already in the market are Toyota, Hyundai and Honda. Nevertheless other companies such as the Volkswagen group, Daimler or General Motors are developing their own car as well in order to prepare for the near future.

Fuel cell vehicles have several key factors that may carry the automotive breakthrough in a mid-term period:

- First and foremost, even if hydrogen is produced with fossil fuels, the overall fuel cell vehicle contamination is 50% less than with a conventional internal combustion car. That means that if all cars in a mid-term period were switched to fuel cell vehicles, greenhouse emissions would be drastically decreased. Moreover if hydrogen is obtained by electrolysis and the electricity needed for the process is obtained from renewable sources, no carbon dioxide nor carbon monoxide would be released into the atmosphere making the whole hydrogen cycle completely environmentally friendly.
- Range of fuel cell vehicles nowadays has matched the ranges for internal combustion vehicles and surpassed autonomy range of BEV (Battery Electric Vehicles).
- Hydrogen refueling takes about three minutes, where in the most technologically advanced BEVs loads last up to 20 minutes.

- Average life of a fuel cell stack is 10 to 15 years, which matches the average life of a car in current times, with no need for FC stack replacement.

However some put backs have to be considered too:

- Nowadays hydrogen production is not really clean, and up to 96% of produced hydrogen is obtained from either natural gas, coal or petroleum.
- Hydrogen refueling networks are fare from being well implemented. Currently the number of available hydrogen refueling stations is very limited and therefore FCVs are not available to the major extent of the society.
- Scepticism about safety in fuel cell vehicles is a fact. Even though fuel cell vehicles are now completely safe and have diverse emergency protocols in case of hydrogen leakage, there still exists a general perception that FCVs are not as safe as IC cars or BEVs.

4.1 Elements of an automotive fuel cell system

4.1.1 Hydrogen tank

Hydrogen tanks store the hydrogen in the vehicle at a certain pressure and conditions in order to ease chemical reactions in the fuel cell stack. Regulations establish that pressure in the tanks must be either 700 bar (High pressure) or 300 bar (Low pressure) and while all main leading FCV brands have tank pressures of 700 bar, Honda bets for low pressure tanks in the Honda Clarity. Tanks must be strong and stiff enough to resist both internal and external events that may incur in possible tank damage. Those events may be higher inner pressures than expected, chassis vibrations, possible scratches and cracks, hydrogen leakage, etc.

For that reason tanks are made of composite materials, bestowing lightness and robustness to the whole storage system. Tanks have several layers of several materials in order to tackle those external and internal threats to the normal operation of the tank. Inner layers might be of plastic polymer in order to seal the hydrogen in the tank and outer layers are normally made from carbon fibre reinforced plastics and glass fibre reinforced plastics. When using composite materials overall results regarding strength and performance are enhanced.

In order to match autonomy ranges of internal combustion vehicles, fuel cell vehicles have two or even three hydrogen tanks per vehicle.

4.1.2 Fuel cell stack

The fuel cell stack is the main key component of an automotive fuel cell system. It has the responsibility to generate DC current from the electro-chemical reactions that take place in the fuel cell. As it has been mentioned before in subsection 3.2.3 a single fuel cell offers less than 1 voltage so in order to meet specifications for any possible application it is necessary to pile fuel cells in series into a stack. The amount of power delivered by the fuel cell stack depends on several factors such as cell size, operating temperature, fuel type, pressure of intake gases, etc.

To set as an example, the Toyota Mirai fuel cell stack is now one of the most advanced and innovative in this field. The new 2016 Mirai has an external maximum electric output of 144 kW, a volume power density of 3.1 kW/L and a number of cells in series of 370.

4.1.3 Battery stack

The battery stack in a FCV is a backup element in the drivetrain system, in the way that is responsible for storing energy in decelerations of the vehicle and contribute with an energy boost in accelerations and starts of the vehicle. While some brands as Toyota bet on a nickel-metal hydride battery for the Mirai, Honda has implemented a conventional Lithium ion battery in the Clarity with a maximum voltage capacity of 288 V.

4.1.4 DC Boost converter

The DC boost converter is a device that increases a voltage input to a higher value. In most cases it raises the output voltage from the fuel cell stack or the battery up to 650 V in direct current as required by the HV components. What this means is that more power can be generated having the same current.

Another advantage of having increased power is being able to reduce the number of fuel cells per stack, as well as the number of cells in the battery pack. This has an impact on weight and eventually in overall performance of the FCV.

Below we can see the general scheme for a Boost converter as well as the characteristic waveforms:

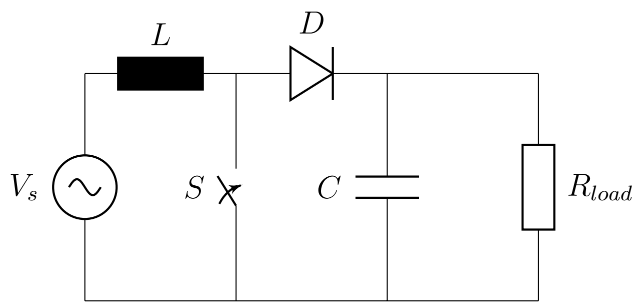


Figure 4.1: Boost converter general scheme

Boost converters face to distinct modes of operation: Continuous and discontinuous mode. In continuous mode the current going through the inductor is never zero and as seen in figure 4.2 the characteristic waveforms are this way:

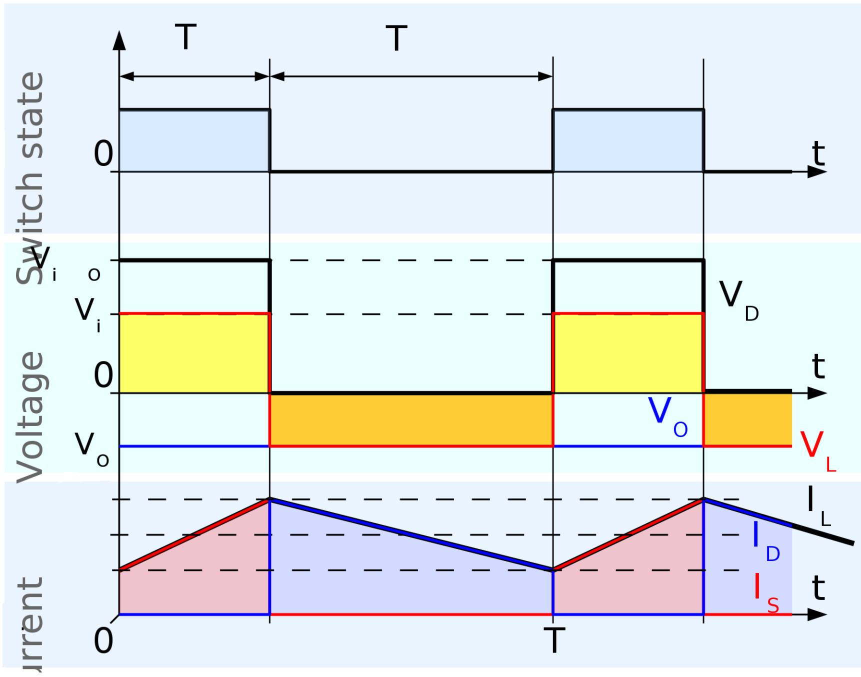


Figure 4.2: Boost converter continuous mode waveforms [6]

In discontinuous mode, the inductor is able to completely discharge before the switching cycle ends and therefore the waveforms are like in figure 4.3.

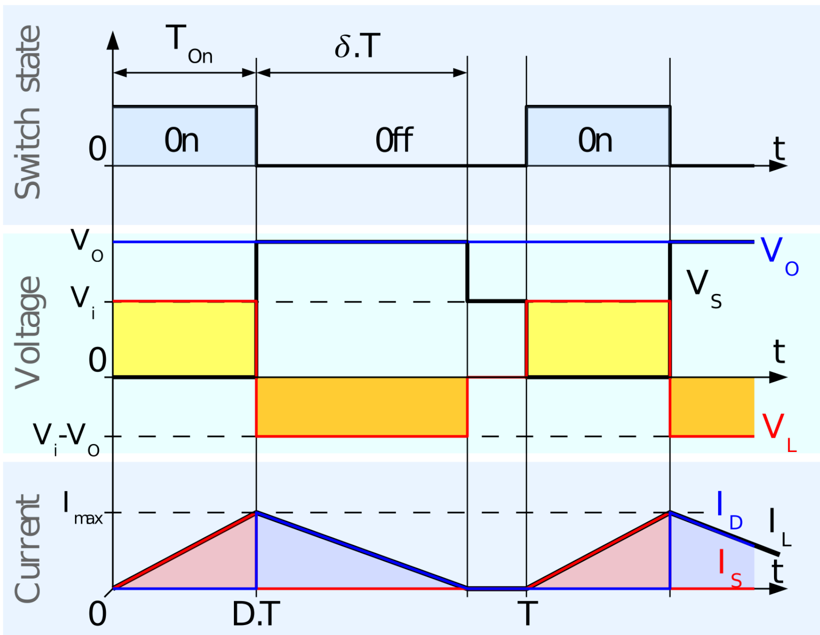


Figure 4.3: Boost converter discontinuous mode waveforms [7]

4.1.5 DC/DC converter

The DC/DC converter is the device in the drivetrain responsible for adapting high voltage obtained either from the batteries or the fuel cell stack into 12 V, which is the normal operation voltage for control electronic devices. Those electronic devices can include from the fuel cell control system to even headlights.

In this case then, it can be said that the DC/DC converter is a step-down converter (Buck converter). The layout for a conventional Buck converter can be seen below, as well as the characteristic waveforms of the device.

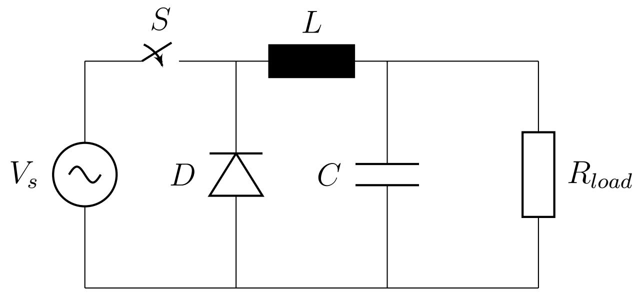


Figure 4.4: Buck converter general scheme

Boost converters face to distinct modes of operation: Continuous and discontinuous mode. In continuous mode the current going through the inductor is never zero,

4.1.6 Inverter

The inverter or DC/AC converter is the device responsible of transforming the DC current obtained in the boost converter after the fuel cell stack to AC current in order to feed the electric motor in the drivetrain system. In order to do that parameters such as output voltage, output frequency, total delivered power have to be specified, and the final design of the converter will vary if those parameters vary.

When decelerating, the inverter has to be capable to obtain the AC current generated in the motor and transform it in DC current in order to feed the battery.

For that reason, it is needed a three-phase inverter, scheme of which is shown below, as well as the characteristic waveforms.

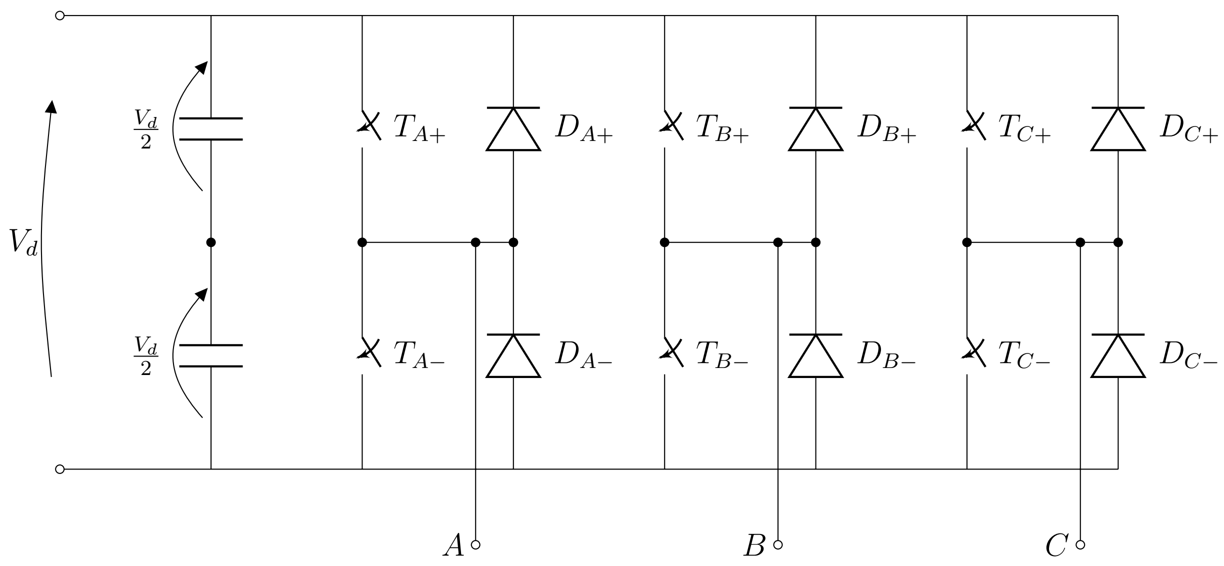


Figure 4.5: Three phase inverter general scheme

An inverter can deliver multiple output waveforms such as:

- Square wave: The simplest kind of waveform an inverter can produce, having transitions depending in the switching frequency of the MOSFETs.
- Modified sine wave: A modified sine wave is the result of adding two or more square waves together. Depending on the number of square waves the phase between them will vary. For instance, let us have a modified sine wave which is the result of adding two different square waves. The phase between them in this case will be of 90°. As a result, we obtain the modified sine wave shown in figure 4.6, which has 4 transitions per period. It is a valid alternative for making approximations to sine waves without the extra cost that this entails.

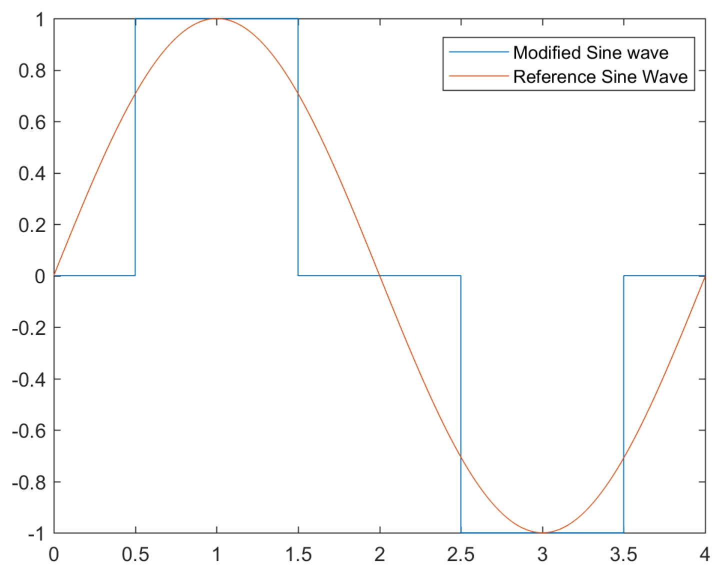


Figure 4.6: Pure sine wave versus three level modified sine wave

- Sine wave: It is very unlikely that an inverter delivers a pure sine wave with no distortion. In much cases, sine waves are highly stepped modified sine waves that eventually work as a pure sine wave. More steps in the output waveform, entail more complicated and therefore more expensive devices.
- Pulse width modulated wave (PWM): Pulse width modulation is a technique in which the duty ratio of the switched is modified in order to vary the RMS voltage value. The aim of this is controlling the electrical power supplied (in this case) to the electric motor of the vehicle. As seen in figure 4.7, pulse width modulated signals are obtained from the control triangle signal and the different phase voltages.

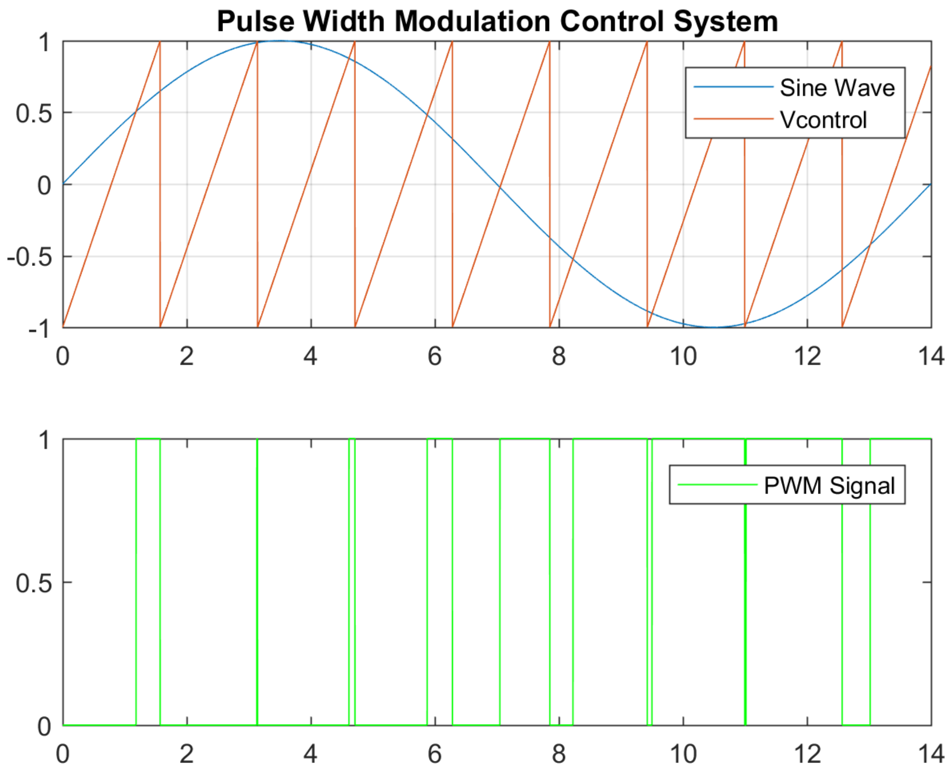


Figure 4.7: Pulse width modulation mode of operation example

4.1.7 Motor

As seen before, fuel cell vehicles obtain electricity to feed an electric motor. Electric motors are divided in two types according to whether they work with direct (PMDC) or alternating current (PMAC). For PMAC motors we can find two different types; Brushless DC Motors (BLDCM) and Permanent Magnet Synchronous Motor (PMSM). but the most used type of motor in automotive solutions due to power/weight ratio, durability and technology knowledge is the Permanent Magnets Synchronous Motor (working with alternate current).While brushless DC motors generate a trapezoidal counter electromotive force when the rotor spins, PMSM generate a sinusoidal force.

PMSMs are separated in two groups according to the position of the magnets within the rotor. In Surface Permanent Magnet Synchronous Motors (SPMSM) the magnets are located in the surface of the rotor while in Interior Permanent Magnet Synchronous Motors (IPMSM) magnets are located inside the rotor.

Either way, those magnets generate a certain magnetic flux. When an electrical input is applied to the stator, a magnetic flux is generated as well and therefore the rotor tends to follow it producing the desired spin. Some materials used for permanent magnets are Samarium-Cobalt (SmCo), Neodimium-Iron-Boron (NdFeB) or ceramic materials ($BaOx_6Fe_2O_3$, $SrOx_6Fe_2O_3$).

Regarding electric drives, there are some variations to take in account. Common configurations are one electric motor either in front or in the rear part of the vehicle, or two motors (rear and back). Current innovations have introduced to this field the four wheel drive vehicles (cars with a motor per wheel, each one with its own transmission and controlled independently by torque vectoring).

4.1.8 Cooling system

In conventional FCV drivetrain systems, two independent cooling systems are used. One is used for cooling the fuel cell stack and the other one to cool the HV components such as the inverter, boost converter and motor.

Having in mind that in a fuel cell is produced both electricity and residual heat, an efficient cooling system is needed. In that way, the cooling system of a fuel cell vehicle in the fuel cell stack resembles a conventional IC cooling system, with a radiator and a pumping system that circulates the cooling fluid between the fuel cell and the before mentioned radiator.

In those systems though, it is possible to produce short-circuits in the fuel cell stack if the cooling system fluid is electrically charged. For that reason an ion exchanger is used, in order to tackle that issue.

4.2 Drivetrain layout comparison

While there are not so many commercial FCV models currently in market, every manufacturer has developed its own powertrain concepts which eventually leads to different powertrain layouts for each model in the market. Below it can be seen how different models implement in different ways the same elements in order to achieve different results.

For example Audi with its concept car h-tron quattro implements a four wheel drive with two electric motors, one in the rear and one in the front. An example as well is the Toyota Mirai, which has a separate boost converter unit while other models implement the boost converter within the power control unit.

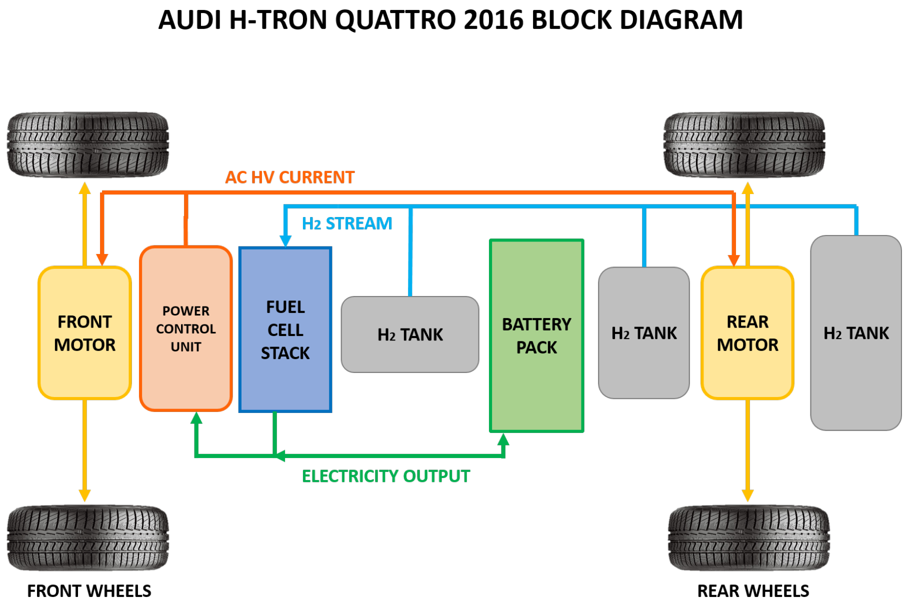


Figure 4.8: Audi h-tron block diagram

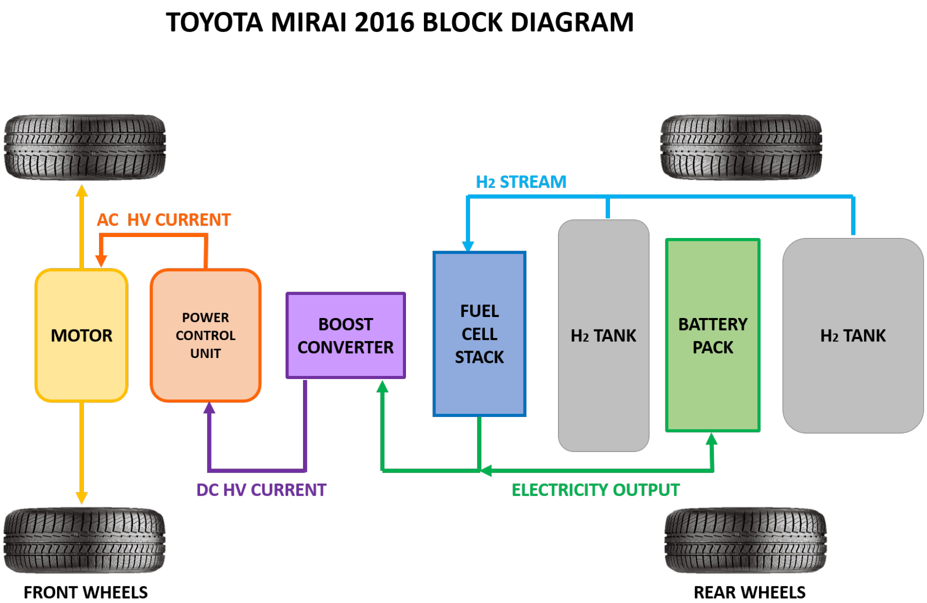


Figure 4.9: Toyota Mirai block diagram

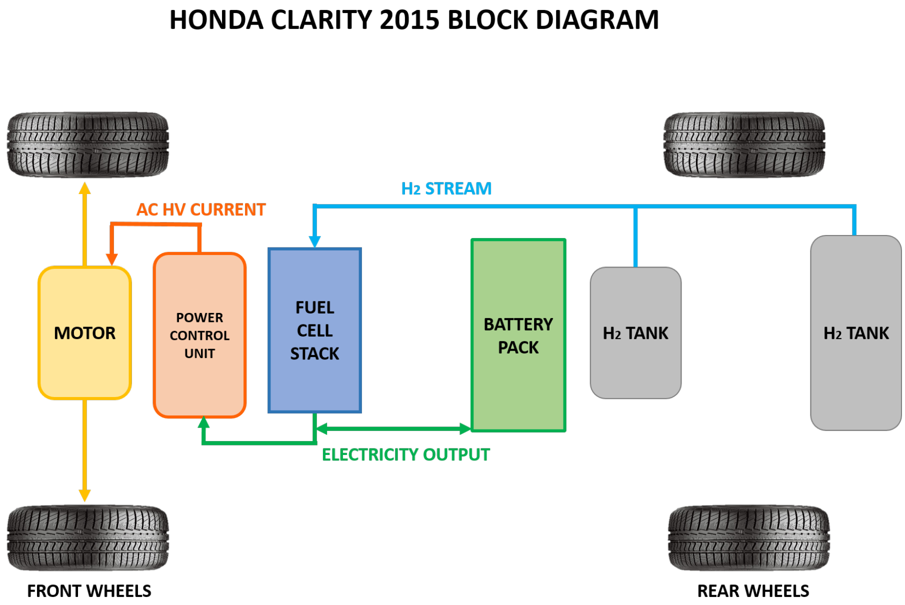


Figure 4.10: Honda Clarity block diagram

4.3 Cost analysis of a FCV

One of the major drawbacks of fuel cell technology right now is the manufacturing cost and therefore, the selling price fuel cell vehicles. Prices nowadays are around $ 50,000 - 60,000 which makes fuel cell vehicles an expensive alternative for personal transportation if compared to conventional IC cars, or even if compared to BEVs.

The reason for that cost is due to the components and technology behind it. Average cost of the main components can be seen in the table below. It has to be noted though that this extracted data is from the year 2007, and reflects the prices of the main components of the fuel cell vehicle in that year. Currently, this prices have gone down as technology through the years has become more reachable for the different automotive companies. For that reason, this table will only be taken in account in a qualitative way, to see in fact which are the most economically relevant components in a fuel cell powertrain system.

Component	Cost [$]
Fuel cell stack	12,000 - 14,000
Battery pack	2,000
Motor and inverter	8,000
Balance of plant	6,000
Tanks and pressure regulator	8,000 - 10,000
Glider	10,000

Table 4.1: Cost of the main components in a FCV drivetrain (Year 2007) [8]

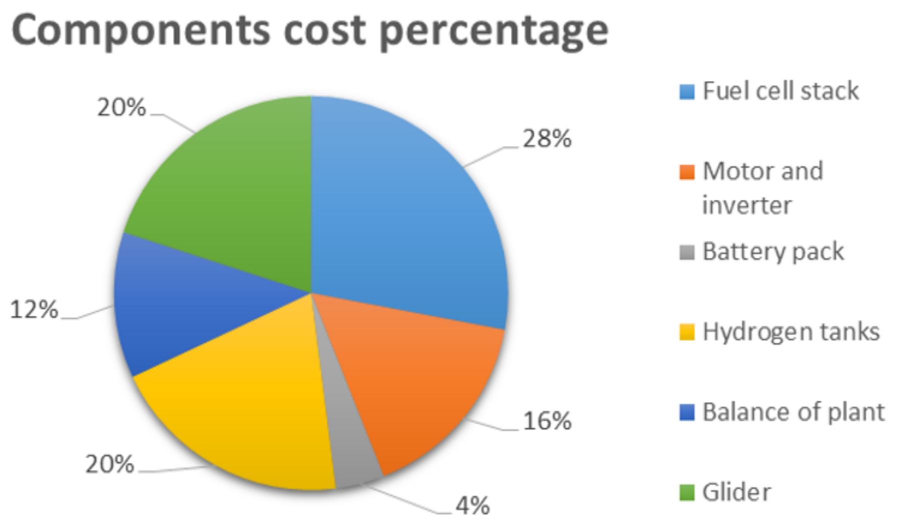


Figure 4.11: Average cost shares for a FCV

As we can see in the figures, the most expensive components are the fuel cell stack, the tanks and the HV system. Fuel cell stack are expensive because of the materials used in the manufacturing process. As commented in the last chapter, fuel cell catalysts are made of platinum alloy and thus they heighten the price, as well as full aluminum machined parts (common mode of encasing the fuel cell stack).

In the same way, tanks are expensive as well as they are hand manufactured with expensive composite materials such as plastic fibre reinforced polymers or carbon fibre reinforced polymers.

While for instance in the tanks there is not much more cost improvement, the introduction of organic membranes in the PEMFC or possible catalysts substituting platinum, could considerably reduce the cost of the fuel cell stack.

5

System Design and Simulations

In order to simulate an entire driving system formed by the fuel cell stack, the DC/DC boost converter, DC/AC converter and PMSM motor, a software such as Matlab Simulink has been chose. This software allows to implement design level structures in order to model complex systems and then obtain the desired data.

5.1 Fuel Cell Stack

For the fuel cell stack modelling some considerations have been taken in account[1].

5.1.1 Voltage Output for the Fuel Cell Stack

For a conventional PEMFC fuel cell, the output voltage can be obtained through the Nernst equation in order to obtain the reversible potential of the fuel cell. This equation only corresponds to the behaviour for one single fuel cell. Every fuel cell within the fuel cell stack will be driven by this same equation. The corresponding equation is 5.1.

$$E_{cell} = E_{0,cell} + \frac{RT}{2F} \cdot ln\left(\frac{P_{\mathrm{H_2}} \cdot P_{\mathrm{O_2}}^{0.5}}{P_{\mathrm{H_2O}}}\right) \tag{5.1}$$

Which can also be written as follows in equation 5.2, assuming that the outcome of H_2O is in liquid form as in conventional fuel cell vehicles, water in the fuel cell comes out in liquid form.

$$E_{cell} = E_{0,cell} + \frac{RT}{2F} \cdot ln(p_{\mathrm{H_2}} \cdot p_{\mathrm{O_2}}^{0.5}) \tag{5.2}$$

$E_{0,cell}$ stands for the reference base potential, and at the same time, this potential is function of temperature and can be expressed by the following equation 5.3.

$$E_{0,cell} = E^{\circ}_{0,cell} - k_e \cdot (T - 298) \tag{5.3}$$

Where $E^{\circ}_{0,cell}$ stand for the standard reference cell potential (at 1 atm and 25 °Celsius). Also, k_e is an empirical constant corresponding the gain when calculating $E_{0,cell}$, with units $(^{\circ}K)^{-1}$.

[1]All equations and constants have been extracted from reference [9]

Nevertheless, it has to be considered that this is the internal output voltage for a PEMFC, and for this reason several voltage drops and effects have to be subtracted. For instance, there are several delays in the fuel and in the oxidants that can be modelled by the following equation in the Laplace domain 5.4:

$$E_{d,cell}(s) = \lambda_e \cdot I(s) \frac{\tau_e \cdot s}{\tau_e \cdot +1} \tag{5.4}$$

Besides the effect of the fuel and oxidant delays, some voltage drops have to be considered. In a PEMFC voltage output function, there will be considered the following voltage drops as explained in the equation below 5.5.

$$V_{cell} = E_{cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell} \tag{5.5}$$

where $V_{act,cell}$ stands for the activation voltage drop (activation losses), $V_{ohm,cell}$ for ohmic voltage drop (ohmic losses) and $V_{conc,cell}$ stands for concentration voltage drop (concentration losses). Next section goes through the equations of the voltage drops and final modelling of the electrical system of the fuel cell stack.

5.1.2 Voltage Drops for the Fuel Cell Stack

Voltage drops can be calculated as follow:

- Activation losses: Activation voltage drop is function of both current and temperature in the PEMFC and its behaviour is described by the Tafel equation, described below in 5.6:

  $$V_{act} = T \cdot (a + b \cdot ln(I)) \tag{5.6}$$

  where a and b are empirical parameters. Equally, V_{act} can be described as $V_{act} = V_{act1} + V_{act2}$, where V_{act1} can be described as the part of the activation voltage drop that is invariant to current (only affected by temperature) and V_{act2}, which is both current and temperature dependant.

- Ohmic losses: Ohmic losses can be described by the following equation:

  $$V_{ohm,cell} = I \cdot R_{ohm} \tag{5.7}$$

  where R_{ohm} is:

  $$R_{ohm} = R_{ohm0} + k_{RI} \cdot I - k_{RT} \cdot T \tag{5.8}$$

  with k_{RI} and k_{RT} being the empirical parameters when calculating R_{ohm}.

- Concentration losses: Concentration losses can be calculated by the following equation, function of the current through the fuel cell.

  $$V_{conc} = -\frac{RT}{zF} \cdot \ln\left(1 - \frac{I}{I_{limit}}\right) \tag{5.9}$$

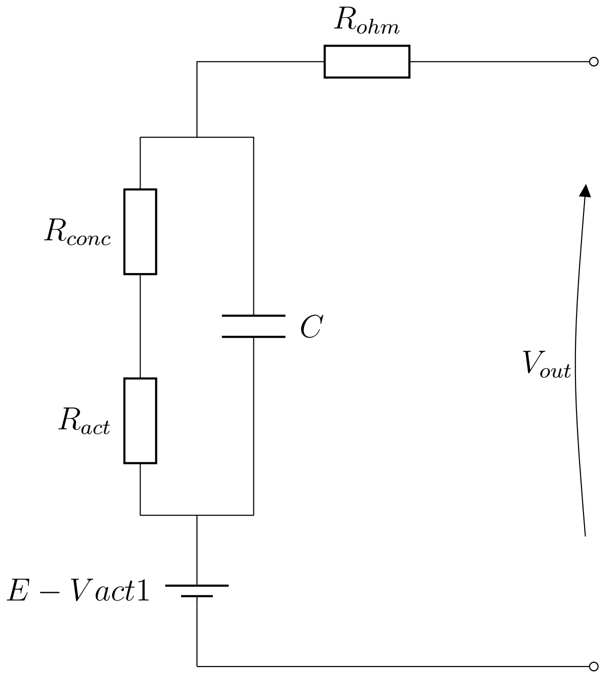


Figure 5.1: Double layer charge effect in a fuel cell

This voltage drops cannot be modelled straight ahead. There is one effect more that has top be taken into account. This is the called double-layer charge effect. This effect is due to the architecture of the PEMFC, as the electrodes are separated by a membrane and this lead the layers in between the membrane behave like a capacitance. This effect only affects the part of the activation losses that is both current ad temperature dependant, and the concentration losses, but doesn't affect neither the ohmic losses nor the temperature dependant part of the activation losses (as seen in the figure below).

From this scheme we can deduce that the output voltage for the fuel cell may then be:

$$V_{out} = E - V_{act1} - V_c - V_{ohm} \tag{5.10}$$

where V_c stands for the voltage throughout the capacitance, which can be expressed as:

$$V_c = \left(I - C \cdot \frac{dV_c}{dt} \right) \cdot (R_{act} + R_{conc}) \tag{5.11}$$

With all the equations listed above a proper electrical model for a fuel cell can be designed. However, this model will depend on the inputs of both temperature and current to work properly. For that reason, thermodynamical equations will be implemented in order to make the system more accurate and temperature non-dependant (as seen in 5.1.3).
One can observe below a figure regarding the electrical modeling of the fuel cell and how this model has been implemented in Simulink.

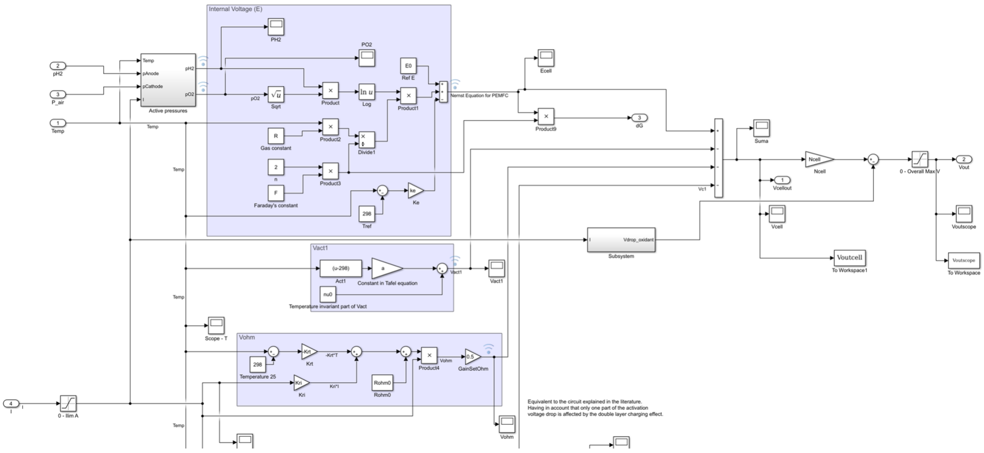


Figure 5.2: Part of the electrical system of the PEMFC model

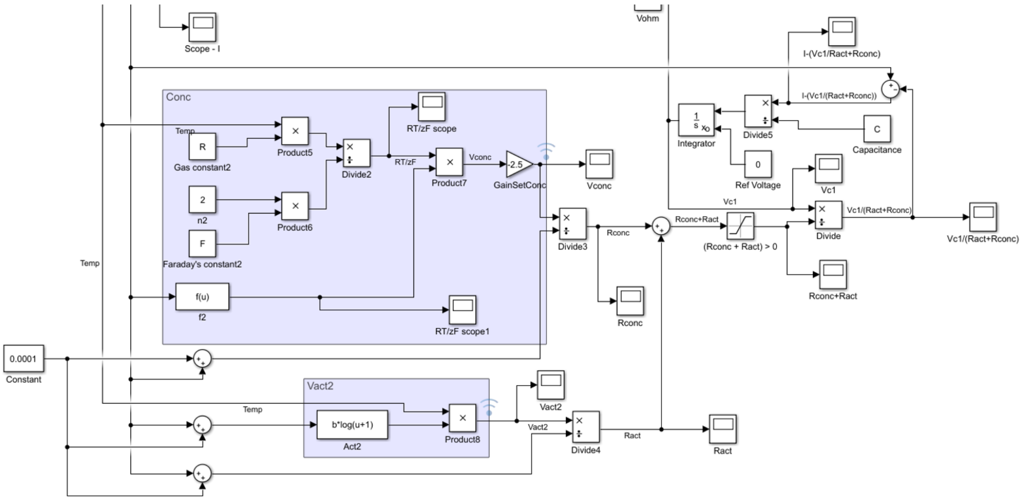


Figure 5.3: Part of the electrical system of the PEMFC model

5.1.3 Thermodynamical Equations

As seen in subsection 5.1.1, voltage in the fuel cell is temperature dependant and that affects to the electrical output of the fuel cell stack and many other parameters of a fuel cell (such as voltage drops) and eventually, to the performance of that system. For that reason, modelling a structure capable of taking in account and controlling the temperature in an accurate way.

In order to model the thermal model of the fuel cell, a simple heat balance is made following the laws of thermodynamics. The heat losses and the generated heat have to be taken in account. The equation below shows the balance (see equation 5.12).

$$\dot{q}_{out} = \dot{q}_{cell} - \dot{q}_{elec} - \dot{q}_{sens+lat} - \dot{q}_{convection} \tag{5.12}$$

In order to obtain the heat from the fuel cell it is necessary to calculate first the Gibbs energy of this same fuel cell, which can be calculated as follows:

$$\Delta G = -E \cdot n \cdot F \tag{5.13}$$

Once the Gibbs energy is obtained, $\bar{q}_{chem}$ can be calculated using the equation listed below:

$$\dot{q}_{chem} = \frac{k_{cell}}{2F} \cdot \Delta G \cdot I \tag{5.14}$$

..

Besides, the heat due to the electrical consumption $\bar{q}_{elec}$ can bhe calculated like this:

$$\dot{q}_{elec} = V_{out} \cdot I \tag{5.15}$$

For the case of the losses $\dot{q}_{convection}$ due to convection, the calculations go like listed below:

$$\dot{q}_{convection} = h_{cell} \cdot (T - T_{room}) \cdot N_{cell} \cdot A_{cell} \tag{5.16}$$

Finally, for the calculations regarding $\dot{q}_{sens+lat}$ the formula can be seen below:

$$\dot{q}_{sens-lat} = (T - T_{room}) \cdot \left[\left(\frac{I}{2F} \cdot C_{p\mathrm{H_2}} \right) + \left(\frac{I}{4F} \cdot C_{p\mathrm{O_2}} \right) + \left(\frac{I}{2F} \cdot C_{p\mathrm{H_2O}} \right) \right] + \frac{I}{2F} \cdot H_{v\mathrm{H_2O}} \tag{5.17}$$

When all losses are calculated, the balance is made and heat can be integrated in order to obtain the output temperature like so:

$$M_{FC} \cdot C_{FC} \frac{dT}{dt} = \dot{q}_{out} \tag{5.18}$$

Where M_{FC} is the mass of the whole fuel cell stack and C_{FC} is the total specific heat of the fuel cell stack. Once achieved this part of the modelling temperature can bee fed back into the electrical model. In this way, a load current dependant model can be obtained. A figure of the thermal model can be seen below.

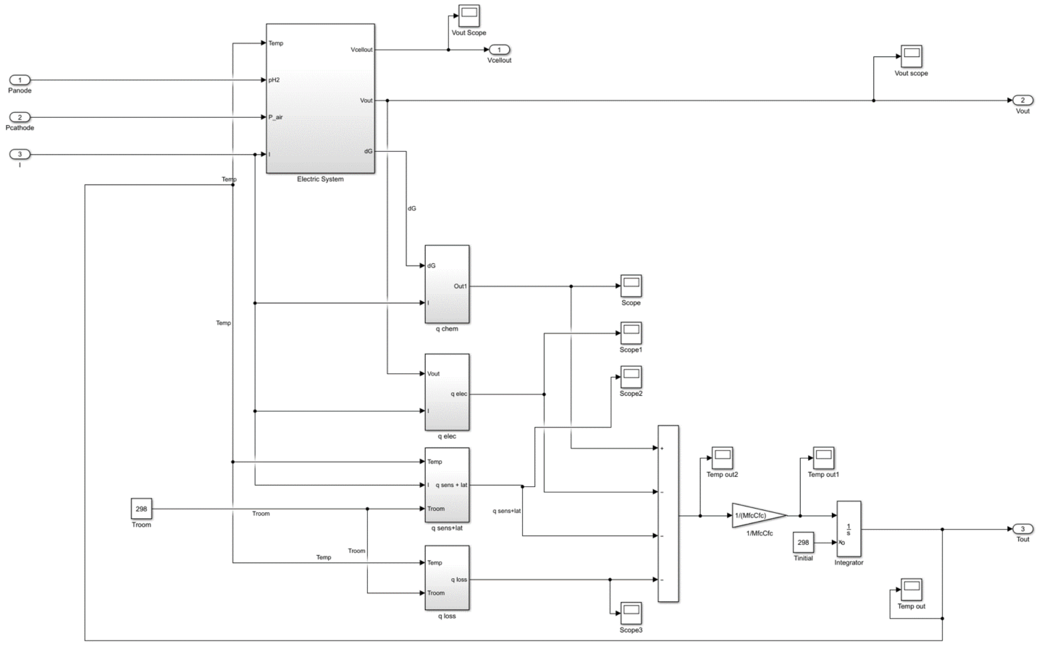


Figure 5.4: Part of the electrical system of the PEMFC model

5.2 Boost converter

For the modelling of the Boost converter, the basic structure has been implemented in Simscape, an electric modelling tool from MATLAB Simulink. As seen in the figure below the first simulation was implemented with a load and a pulse generator in order to test the appropriate duty cycle range for the voltage that is required.

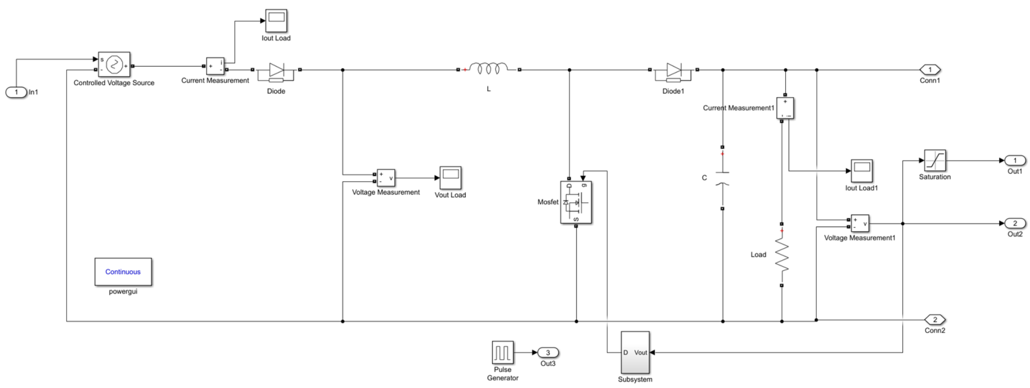


Figure 5.5: Model of the boost converter with a load

In order to get a proper output arranged to 650V, a voltage control can be implemented affecting the duty cycle of the switch in the boost converter. Output voltage is compared to the reference voltage one wants to obtain

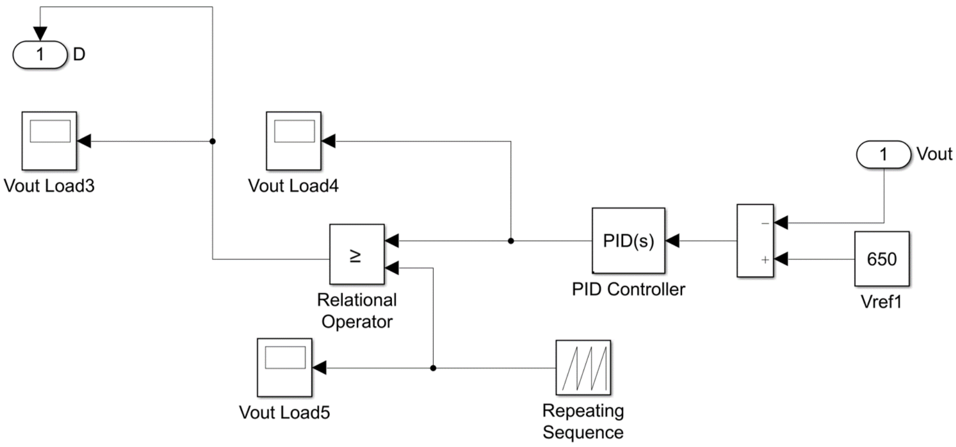


Figure 5.6: Model of the boost controller

As can be seen in figure 5.6, error in the output voltage can be calculated and corrected with the proper PID controller which allows us to obtain the control signal. Once obtained, the control signal can be compared with a reference sawtooth signal in order to adjust the duty cycle up or down so the voltage output can reach the desired voltage reference.

Converter's design parameters can be calculated as follows, knowing the output desired voltage and voltage input range, as well as desired power transfer:

The maximum duty cycle ratio is given by the equation 5.19, which can be found below.

$$D_{MAX} = 1 - \frac{V_{in_{MIN}} \cdot \eta_{converter}}{V_{out}} \tag{5.19}$$

For the inductance selection, equation 5.20 can be used. With that equation, the minimum value for the boost converter inductance can be found.

$$\frac{V_{IN} \cdot (V_{OUT} - V_{IN})}{\Delta I_L \cdot f_s \cdot V_{OUT}} \tag{5.20}$$

The procedure for setting the capacitor value is the same as above, deciding on a minimum capacitor value depending in values in equation 5.21.

$$\frac{I_{MAX} \cdot D_{MAX}}{f_s \cdot \Delta V_{ripple}} \tag{5.21}$$

Once all components are dimensioned, basic structure for the boost converter can be implemented.

5.3 Power systems

The power systems of a fuel cell vehicle are the battery (Li-ion), the inverter and the motor. The battery is set after the boost converter in order to take advantage of the risen voltage, and manage energy charge and discharge of the system. Therefore, the battery is set in parallel between the boost converter and the inverter. Nominal voltage of the battery is set as the value obtained in the output of the boost converter. Battery capacity is then set with this nominal voltage and the power that is to be needed. Further below in figure 5.7 one can see the discharge curve for the chosen model to implement in the electric system with the capacity, voltage and power parameters matching the criteria stated above.

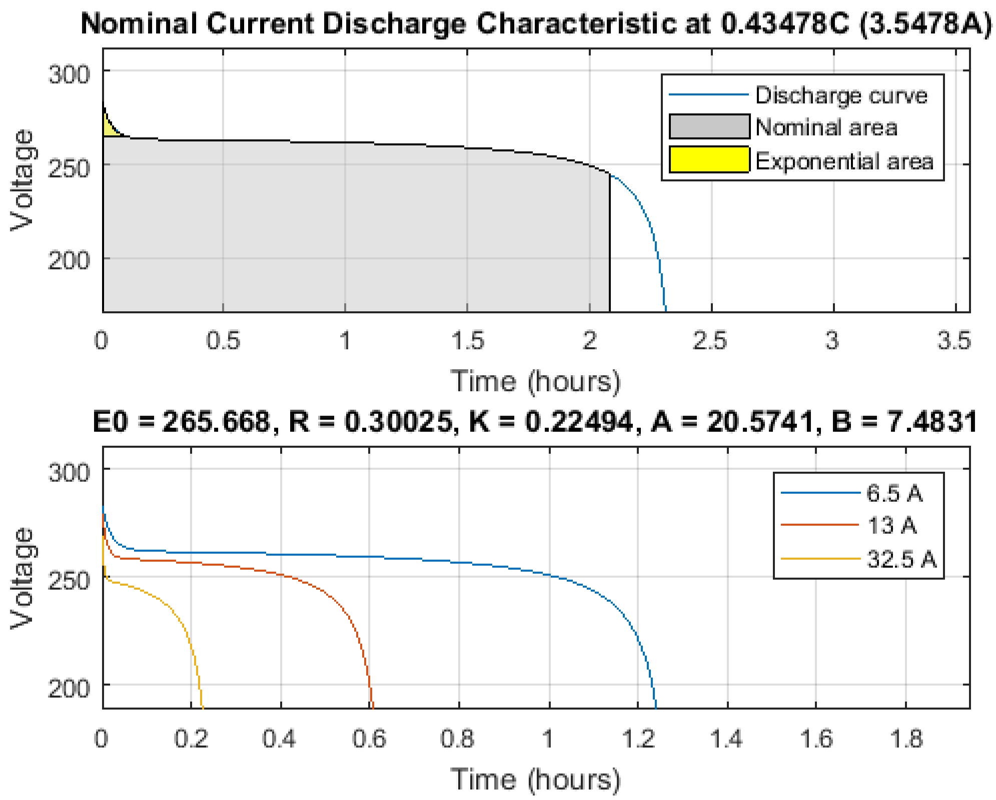


Figure 5.7: Discharge curve for the chosen Li-ion battery configuration

When implementing the motor-inverter structure, a motor model is selected. In this case just a 3kW peak power motor is required and motor parameters can be subtracted. This parameters such as stator resistance, motor inductances and flux linkage can be set into the inverter model in order to link those two elements.

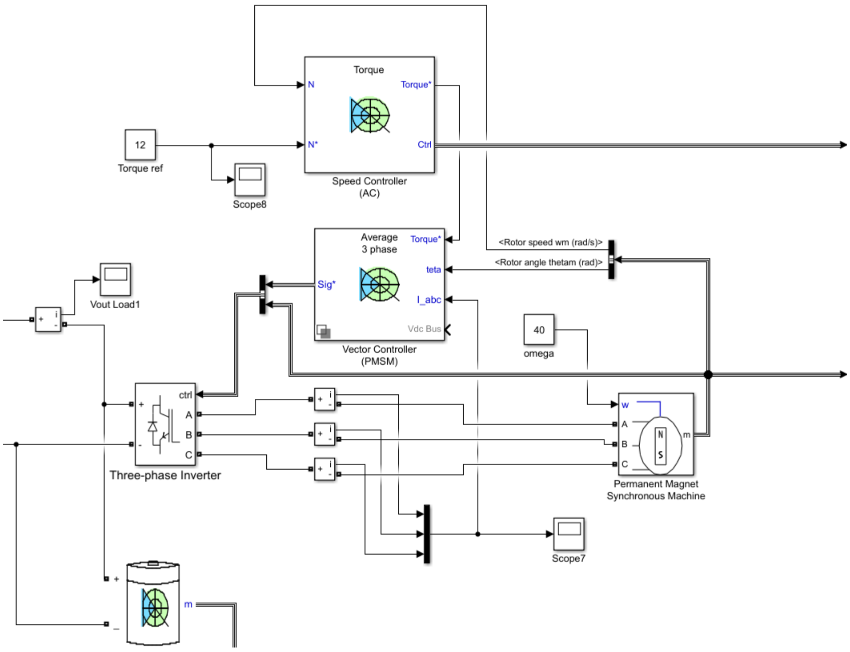


Figure 5.8: Power systems structure

However, these elements need to be controlled and for that, a speed and current control has to be implemented. As shown in figure 5.9 a speed and vector controller is implemented, taking the motor speed, obtaining the required torque and then obtaining the current control in order to drive the inverter.

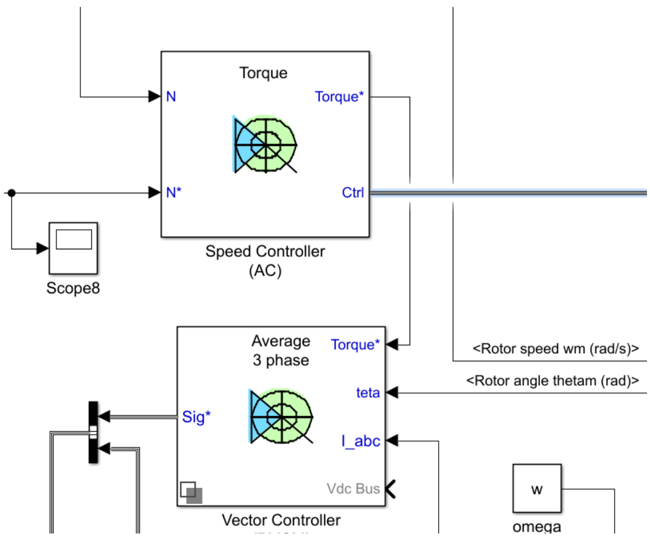


Figure 5.9: Control block of power system

From this system, several data can be retrieved such as electromagnetic torque, and rotor current and voltage as well as rotor speed.

5.4 Dynamic model

In order to test the system in real conditions once it has all been modelled, it has been decided to put this system through a driving cycle consisting in an acceleration ramp, a velocity maintaining phase and a deceleration ramp between 0 and 45 km/h, as the object of study is a vehicle with small power output, such a scooter or a tuk-tuk.

In order to do that, several equations have to be implemented in what is called the dynamic model of the vehicle. That means that the force balance is implemented in order to get the force required by the wheel and eventually, both torque and angular speed in order to be able to control the electrical system of the vehicle.

When implementing the dynamic model of the vehicle, several assumptions have been made, such as considering the vehicle a rigid body with only one axis affected by the forces that intervene in the system. Hence, the equation in which the model will be based is Newton's second law of motion which says that the acceleration of an object as produced by a net force is mass times proportional in the same direction to this same force. In the case of the system in study, the resulting force can be written as the forces that help the vehicle accelerate (tractive forces) and the forces that make the vehicle decelerate (resistive forces). All that can be written as in equation 5.22[2].

$$m \cdot a = m \cdot \dot{v} = m \cdot \frac{d}{dt}v(t) = F_t(t) - F_r(t) \tag{5.22}$$

From equation 5.22 can be seen that tractive forces equal mass product acceleration and the sum of all the resistive forces, as in equation 5.23. From this point on tractive forces will be considered as the force that the wheel produces in order to give the car the certain acceleration required at any time by the vehicle.

$$F_t(t) = F_{wheel}(t) = m \cdot \frac{d}{dt}v(t) + F_r(t) \tag{5.23}$$

Below in figure 5.10 it can be seen how the general structure for the dynamic modelling of the vehicle has been implemented. Following these equations one can obtain the power required by the wheels. Once the power is obtained and the angular speed has gone through the gearbox, the torque can be obtained.

[2]Literature study in this part of the thesis done in reference [10]

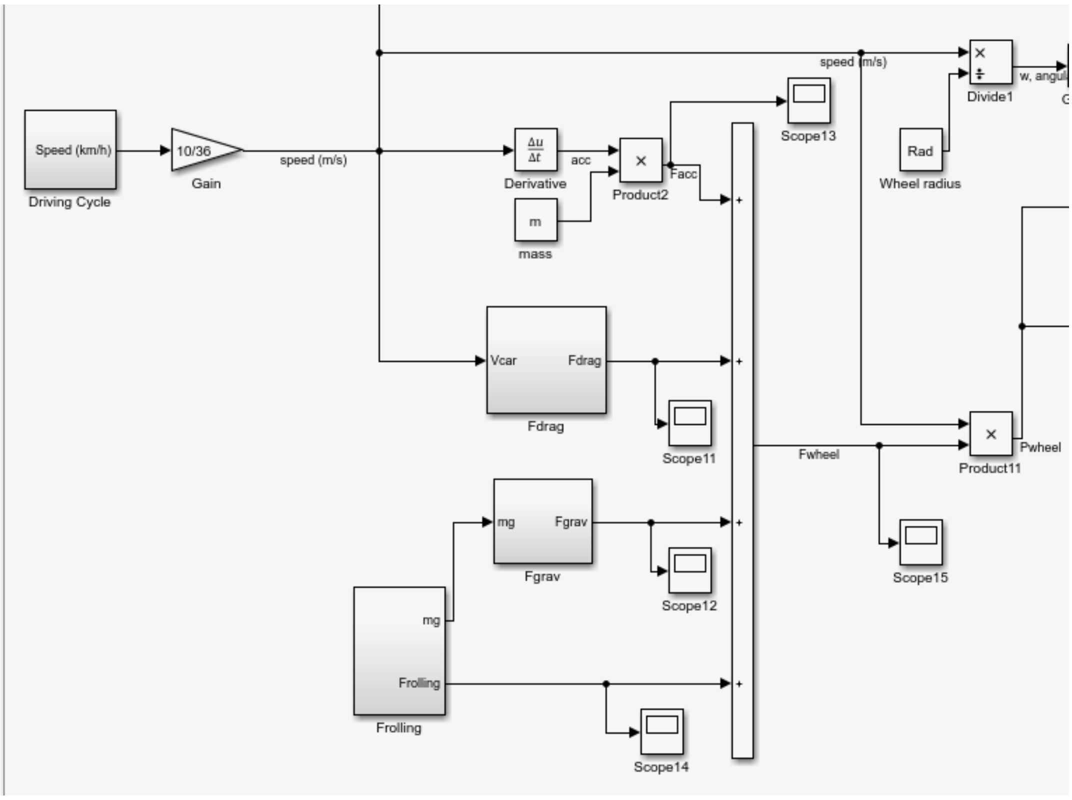


Figure 5.10: Dynamic Model Implementation

Several forces can be described as resistive, in which the aerodynamic drag, the rolling force and the grading force can be included.

- Aerodynamic drag is the force to which any moving vehicle is exposed when moving through air. Having an accurate model for the drag force is relatively complicated so a mathematical formula is used instead in order to describe in a simpler way an acceptable behaviour of the aerodynamic drag. The formula can be seen below in equation 5.24, where ρ_a corresponds to air density, C_d corresponds to drag coefficient, A_f to the cross-section of the vehicle (area of the vehicle actually exposed to the air flow), and v_{wind} the speed of the wind in the opposite direction to the movement of the car.

$$F_d = \frac{1}{2} \cdot \rho_a \cdot C_d \cdot A_f \cdot (v_{car} - v_{wind})^2 \tag{5.24}$$

In figure 5.11 one can see how the drag resistive force equation has been implemented.

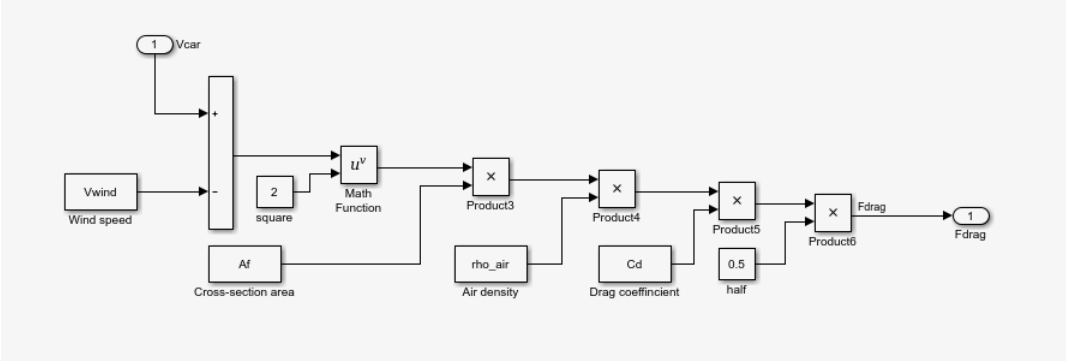


Figure 5.11: Aerodynamic drag force implementation

- Rolling force is due to all effects actuating in the tire while in motion (in other words, while rolling). These effects are considered in the rolling coefficient (C_r), which is function of the tire temperature, speed, material and inflation among other characteristics. The rolling coefficient has been narrowed empirically, as well as its behaviour. It has been proofed that increasing the rolling speed, the rolling coefficient also increases. For a lower speed range, C_r increases slightly. However, while increasing speed to higher values, C_r increases at almost square times the speed.

  On the other hand, tire inflation and temperature have a reverse effect in the rolling coefficient, where to higher tire pressures and higher temperatures, lower values for C_r are obtained. In all the formula for the rolling for in a vehicle can be written as in equation 5.25.

$$F_r = m \cdot g \cdot C_r \cdot cos(\alpha) \tag{5.25}$$

  Rolling force implementation structure in Simulink can be seen down below in figure 5.12.

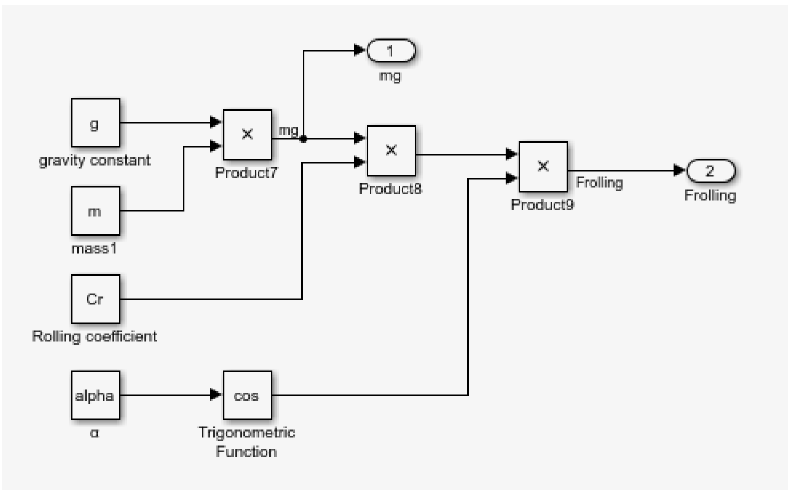


Figure 5.12: Simulink implementation of the rolling force of a vehicle

- Grading force appears when having a particular slope in the road, and it is the component of the gravitational force of the vehicle in the horizontal plane of the vehicle. In this way, having more slope in the road increments this force and of course, decreasing the slope has a diminishing effect in the rolling force. The equation for this force can be found below in 5.26 where alpha is the inclination angle between the road and the horizontal plane.

$$F_g = m \cdot g \cdot sin(\alpha) \tag{5.26}$$

Grading force implementation can be seen below in figure 5.13

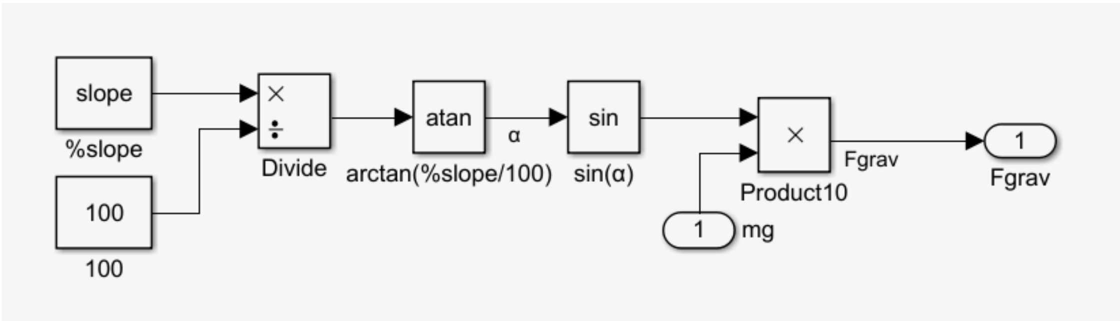


Figure 5.13: Simulink implementation for the grading force of a vehicle

Alpha angle can actually be written as an expression between the vertical distance and the horizontal distance such as in formula 5.27

$$\alpha = arctan\left(\frac{rise}{run}\right) = arctan\left(\frac{slope(\%)}{100}\right) \tag{5.27}$$

Implementing all these equations in a Simulink model will eventually grant the chance to obtain the resulting force on the wheel and, with that and the linear speed, the overall power in the wheel can be obtained, as shown in equations 5.23 and 5.28.

$$P_{wheel}(t) = F_{wheel}(t) \cdot v(t) \tag{5.28}$$

Nevertheless, the designed model has as input reference both torque (Nm) and angular speed of the motor. In order to obtain the parameters above mentioned, equation 5.29 can be used, always having in account that the angular speed shall be in between a certain functioning limit as the motor requires. In this particular case, a one stage gearbox has been implemented with a transmission ratio of 5, meaning that angular speed is multiplied by 5 when arriving to the motor. Having this and if power is maintained, less torque is required to match the power requirements.

$$P_{wheel}(t) = \Gamma_{wheel}(t) \cdot \omega(t) \tag{5.29}$$

Having the driving cycle and the wheel radius of the vehicle in study, angular speed can be easily obtained and therefore torque can be calculated. Once obtained both angular speed and torque, this values can be inputted respectively in the motor controlling and the speed controller for the inverter in order to give the driving cycle reference to the system.

In table 5.1 one can see the chosen values for the different dynamic constants, taking in account all made considerations.

Constant [Unit]	**Value**
Wind speed [m/s]	0
Cross section [m^2]	1.8
Air density [kg/m^3]	1.225
Rolling coefficient	0.012
Drag coefficient	0.27
Slope [%]	0
Mass [kg]	250
Wheel Radius [m]	0.2

Table 5.1: Dynamic constants values for the chosen vehicle model

6

Results

When approaching any final stage of modelling of any component of the system, several tests have been done in order to assure the proper functioning of every part and in ultimate instance, the proper functioning of the whole of the fuel cell vehicle. Those results are presented below for each of the modelled elements in the system.

6.1 Fuel cell stack simulation

As seen in figure 6.1 the structure of the fuel cell stack depends in pressures in the cathode and the anode as well as the input current, and delivers an output voltage, output power and output temperature.

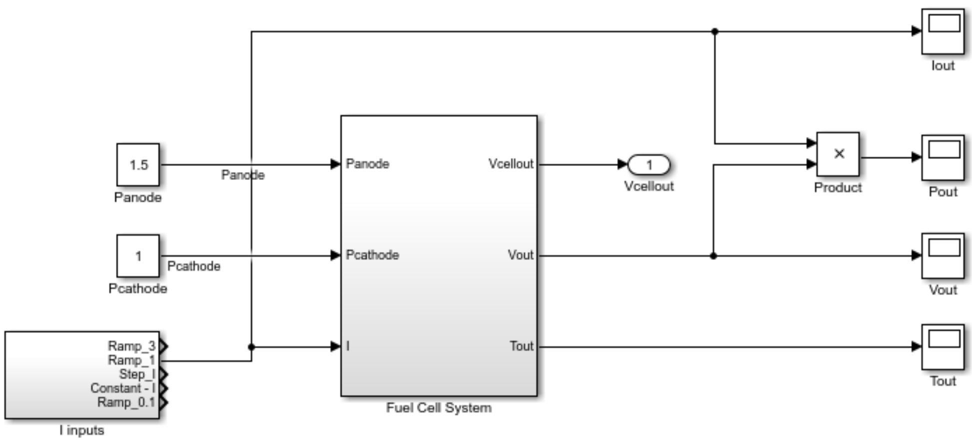


Figure 6.1: Full structure of the PEMFC stack

Nonetheless, as far as this study is concerned temperature will not be evaluated since what it is important in the system is output power and voltage. In order to properly test the system, several current inputs have been set so the response of the fuel cell stack could be observed in different kinds of situations. In all, three types of inputs were set: constant current at a certain value between 0 and I_{lim}, first order step and ramps of different durations and slopes.

Below, in figures 6.2 and 6.3 can be seen the reaction of the fuel cell stack when inputted a constant current of 24A.

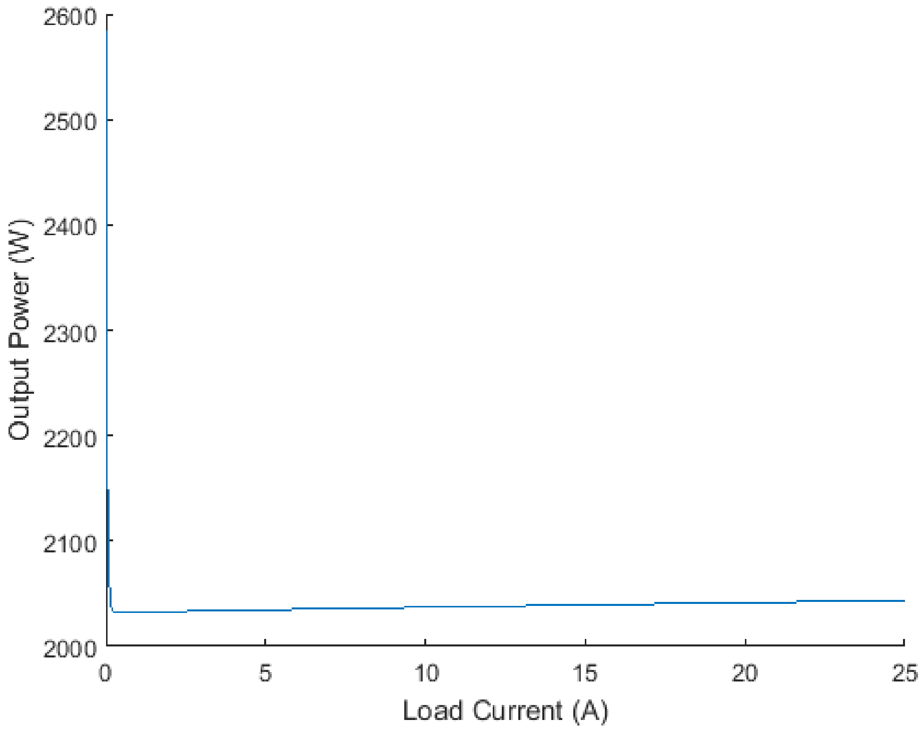


Figure 6.2: Stack power response to a constant current input of 20 A

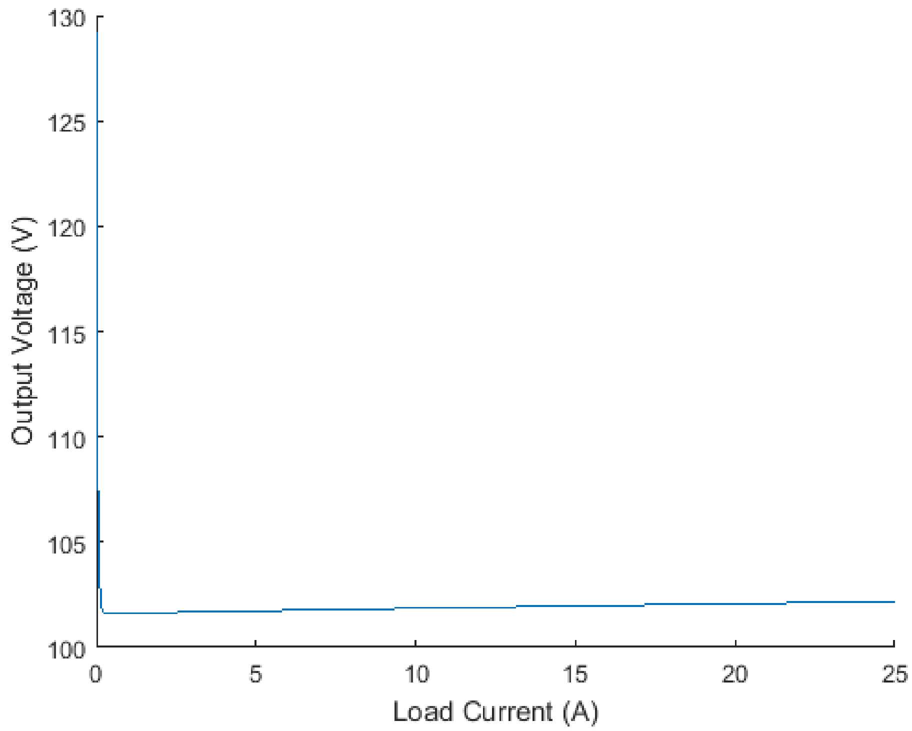


Figure 6.3: Stack voltage response to a constant current input of 20 A

Having these graphics, several conclusions can be extracted. Firstly, it has to be noted that power in this particular situation is just a gained function of voltage, as current remains constant throughout the simulation. When starting the system there is a peak in both voltage and power until voltage drops start affecting the system. At the same time this happens, temperature on the system slowly decreases, decreasing as well the effect of the several voltage drops. This grants a slight rise through time in voltage and therefore, in output power.

On the other hand, we can see in figures 6.4 and 6.5 that different load current within the feasible stack range is applied. When this happens the response of the system is completely different.

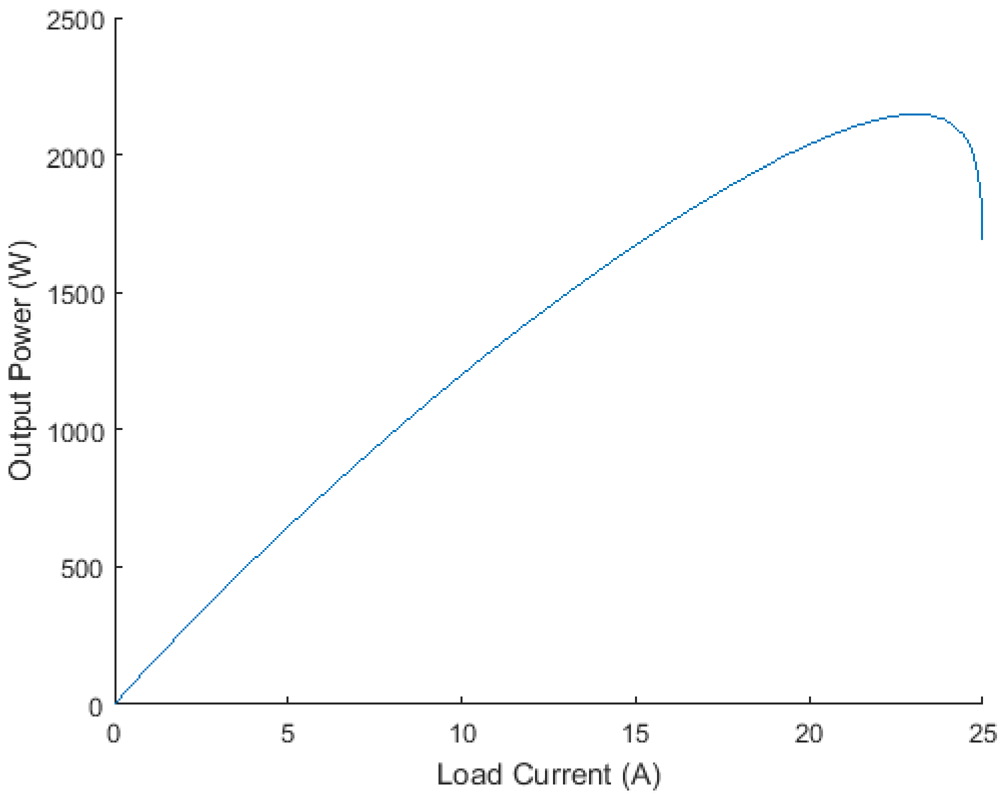


Figure 6.4: Stack power response to a linear variation in load current

Power in a fuel cell has two different behaviours depending on which side of the peak fuel cell stack point point we are situated. If situated left, it can be seen that the power increases as load current increases.

However, past the peak power point, the fuel cell stack enters in the concentration zone and therefore, output voltage drops considerably making the power decrease and eventually achieving worse fuel cell stack performance. In normal circumstances the concentration zone should be avoided when working with the fuel cell stack. Therefore, any point past the peak power point in the fuel cell stack should not be considered as proper operating point.

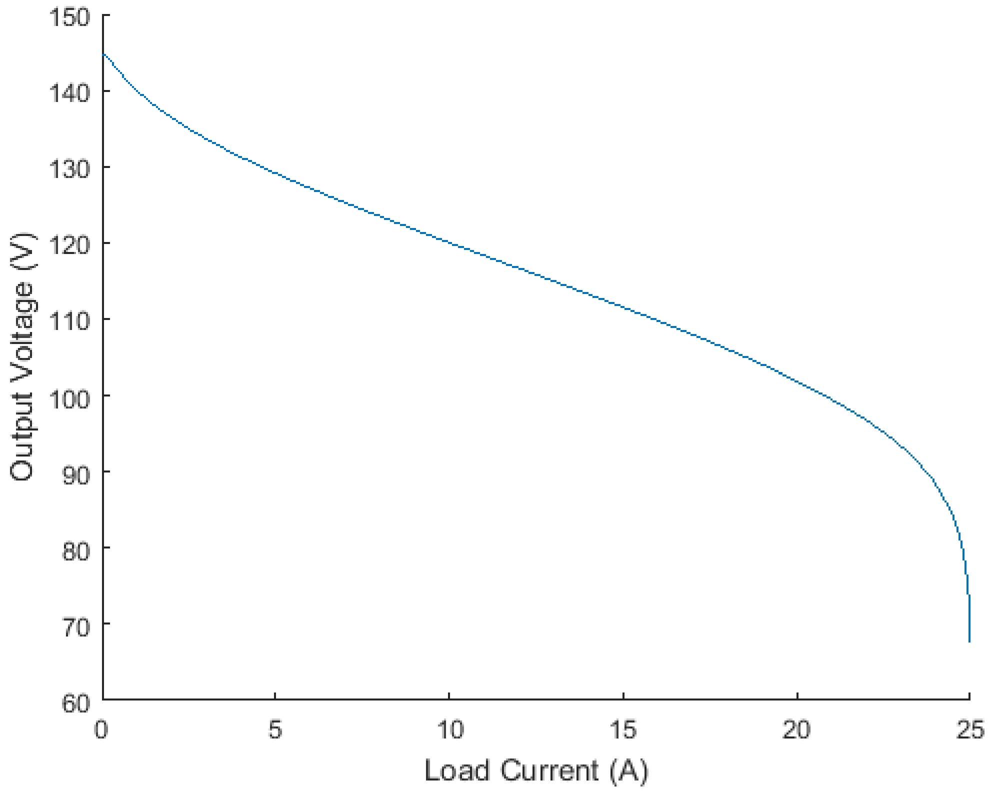


Figure 6.5: Stack voltage response to a linear variation in load current

Regarding the voltage, the graphic shows how in the beginning and the end of the load current progression concentration and activation losses play an important role in the overall voltage drops while in between those zones, ohmic losses are responsible for this semi-linear voltage drop. In this graphic can be appreciated how past the peak power point voltage drops drastically, decreasing output power.

6.2 Boost converter and fuel cell stack

When simulating the boost converter within the PEMFC system, the area of interest will be the output voltage and whether it can be increased or not. Regarding that matter, several simulations have been implemented and the results have been as follow. As it can be seen in figure 6.6, tuning in the PID controller has to be made in order for the output voltage to manage to stay within the given reference (in this case 245V). While after some time the converter is able to reach the said reference, it is quite clear that we may require additional tuning in order to adapt the boost converter to a faster, more accurate response. For that reason, the boost converter has been linearised and implemented in an auxiliary system as a transfer function, in order to automatically tune the PID controller and obtain precise values for k_p, k_d and k_i.

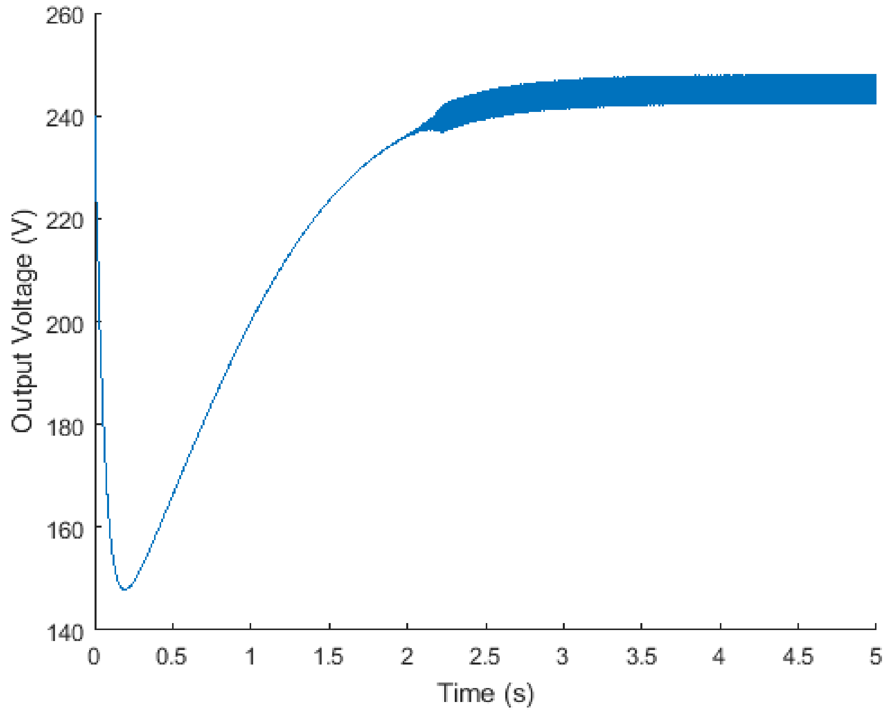


Figure 6.6: Boost converter voltage output curve

With the newly found controller values, another simulation is launched, which results can be seen in 6.7.

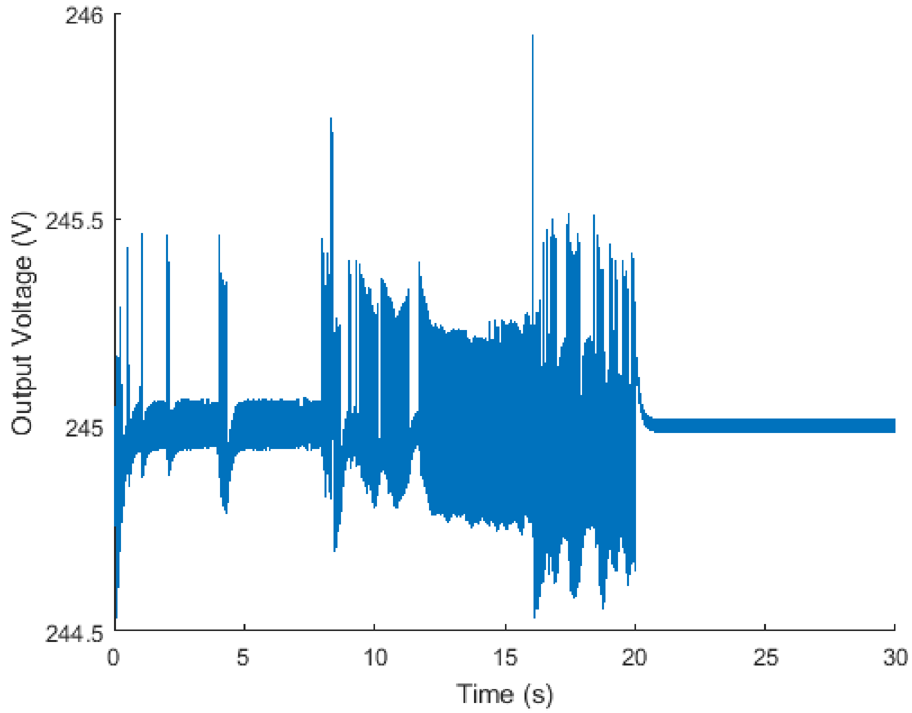


Figure 6.7: Boost converter voltage output curve

As seen in this graphic, controller response is way faster than in the previous PID tuning and variation range is smaller, always keeping a small variancy around 245, the given voltage reference.

However and in case of controller failure, an additional block has been implemented in order to keep the voltage constant within an acceptable range. The output signal has been narrowed between values of 244 and 246 volts. Having this signal, a more accurate functioning of the three-phase inverter can be achieved and eventually, a better functioning of the whole system can be accomplished.

6.3 Power systems

When simulating the power systems of the model, two stages were considered:

- First and once modelled the power systems and its control devices, it was simulated considering a continuous invariant voltage source of 245V, as well as with fixed reference torque and angular speed for the motor, in order to see if the system worked properly without any mistakes, as can be seen in figure 6.8.

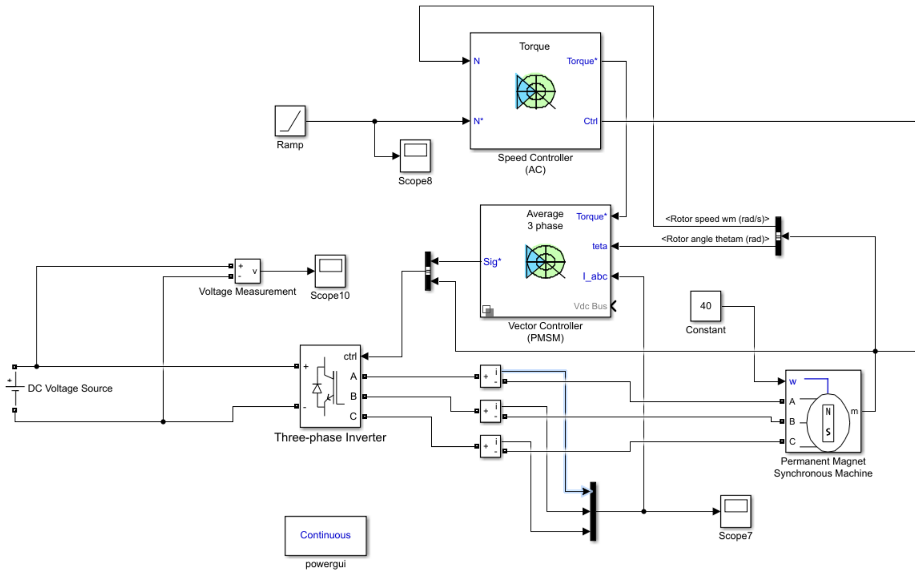


Figure 6.8: Scheme of fixed values power systems test

- Second and only once the model was verified, the power systems of the model were attached to the PEMFC/Boost structure in order to see how the system behaved as a whole. Fixing a speed of the motor and obtaining the power that the fuel cell can give, reference torque can be calculated using equation 6.1. Then the current measurement from the motor can be fed back directly to the fuel cell stack in order close the loop and make steady-state simulations.

$$P = \Gamma_{motor} \cdot \omega_{motor} \tag{6.1}$$

Result for steady-state conditions can be seen below. It has to be taken in account a fixed angular speed of the motor value of 300 rad/s, and a selected motor of 3kW of peak power. Figures 6.9 and 6.10 show the functioning of the three-phase inverter and how the three-phase sinusoidal waveforms are obtained.

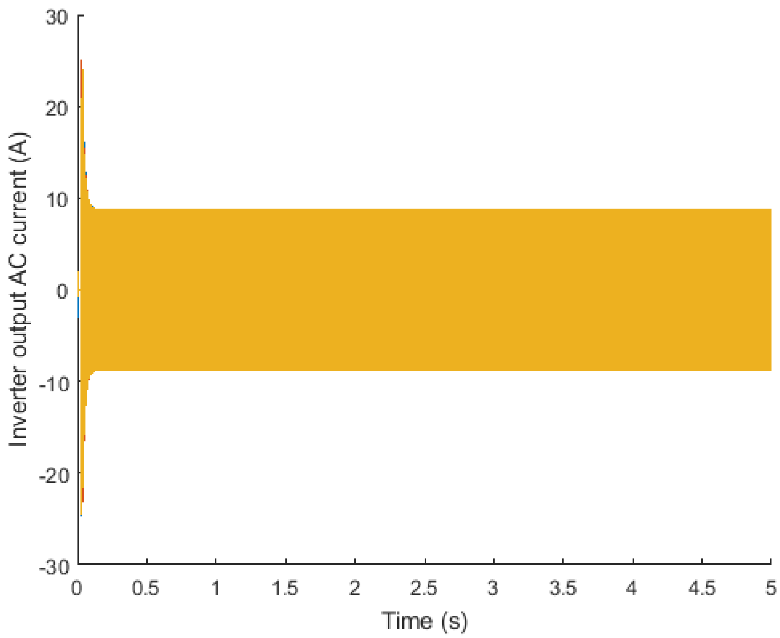


Figure 6.9: Inverter output current

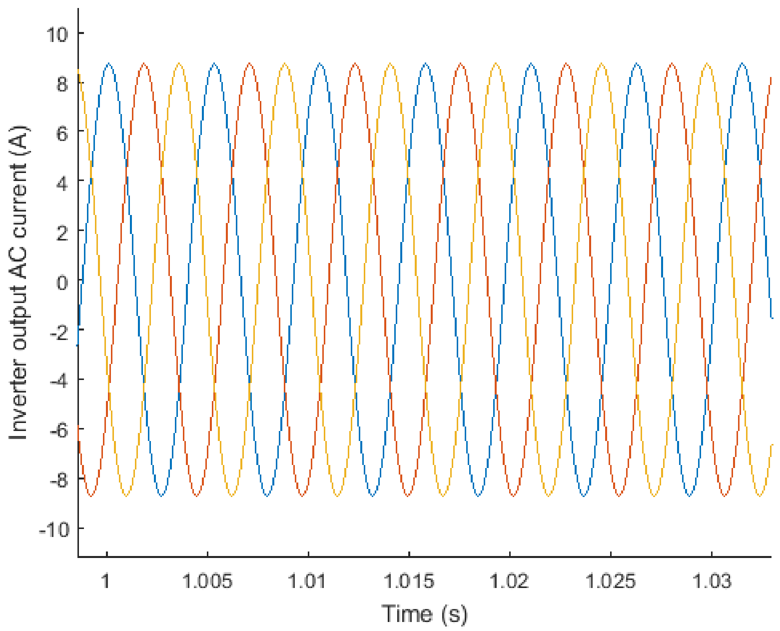


Figure 6.10: Zoomed graph of inverter output current

6.4 Fuel cell vehicle system

In order to test the full model of the vehicle, including the dynamic model and all the electrical system of the vehicle, a driving cycle has been implemented. As the system in test does not give the amount of power a conventional vehicle would supply, a customised driving cycle has been implemented.

As shown in figure 6.11 a first stage of acceleration is implemented, from 0 to 40 km/h. After accelerating, the vehicle will maintain speed at 40 km/h and decrease it down to 0 km/h in the end of the cycle, having a deceleration stage. This linear speed translates into a certain rotor speed in the motor once it is put through the gearbox. With this driving cycle we can actually see how the car and all its systems behave in every situation and if eventually, the electric power supply can feed correctly the motor in order to make the vehicle move.

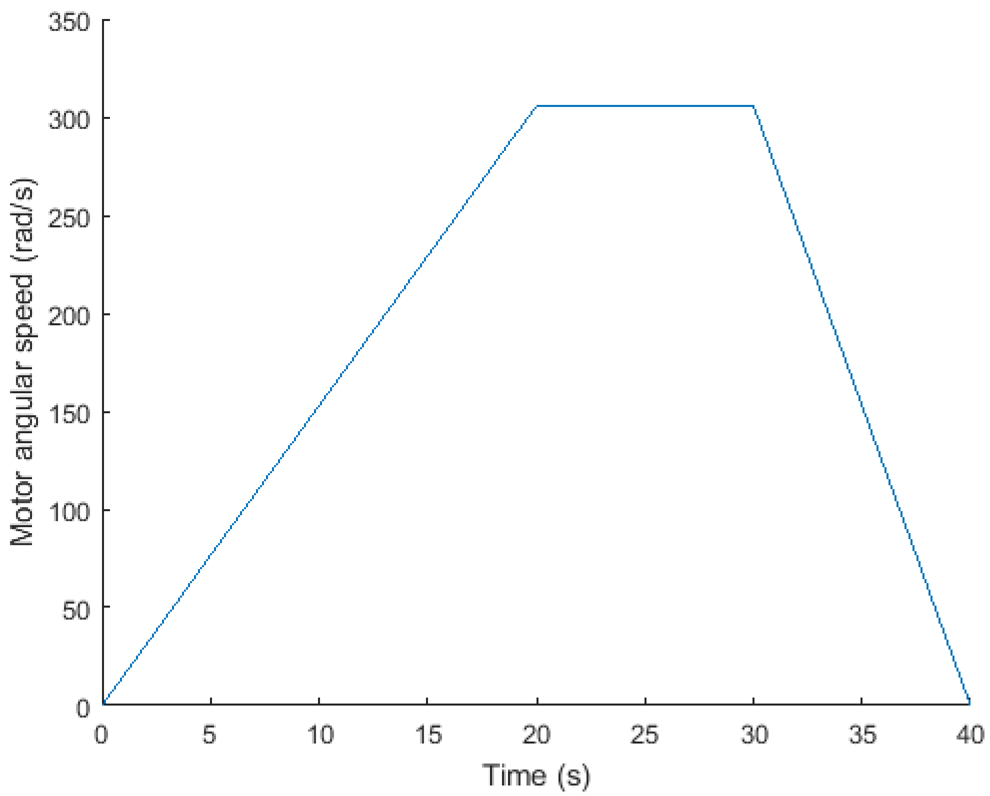


Figure 6.11: Driving cycle implemented as system testing, in the perspective of motor speed request

Simulations can allow us to obtain graphics of different parts of the system, which are shown below. Please note that all figures listed below correspond to the behaviour of several parts of the system when exposed to the above said driving cycle.

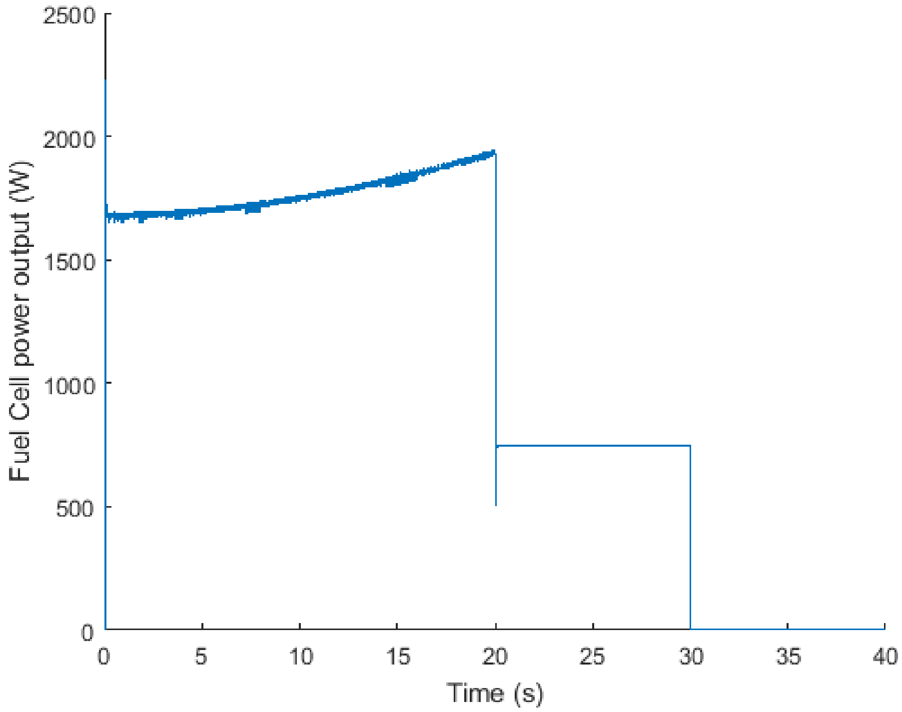


Figure 6.12: Fuel cell stack power output throughout the full driving cycle

As it can be seen in figure 6.12, the power output for the fuel cell stack has, as the driving cycle, three well differently stated parts. As the driving cycle linearly increases speed of the car in the first stage, forces also vary due to this variation in speed. Altogether it results in a semi-linear behaviour for the power output in the fuel cell stack, as this changes in the required power keep requiring more current as time goes forward. Power then increases up to its peak power when the desired maximum speed is reached. This behaviour happens until the next stage of the driving cycle is reached.

As the cycle progresses and we enter in the constant speed region, the current needed is no longer as big as it was when trying to reach this said speed. For that reason, when current decreases in the motor, the power in the motor also decreases causing the fuel cell stack to give less power that in the previous stage, as the system no longer needs that big amount of power anymore. In figure 6.12 can be seen that the approximate power to run the vehicle at a constant speed of 40 km/h goes roughly around 750-800W. Once this stage is completed, we enter in the deceleration stage of the driving cycle.

In the deceleration stage of the driving cycle, the current changes its sign and therefore, the motor acts as a power generator. When the motor starts working as power generator, current is generated instead of wasted so technically the fuel cell stack must not provide any kind of energy and therefore, power must equal to zero.

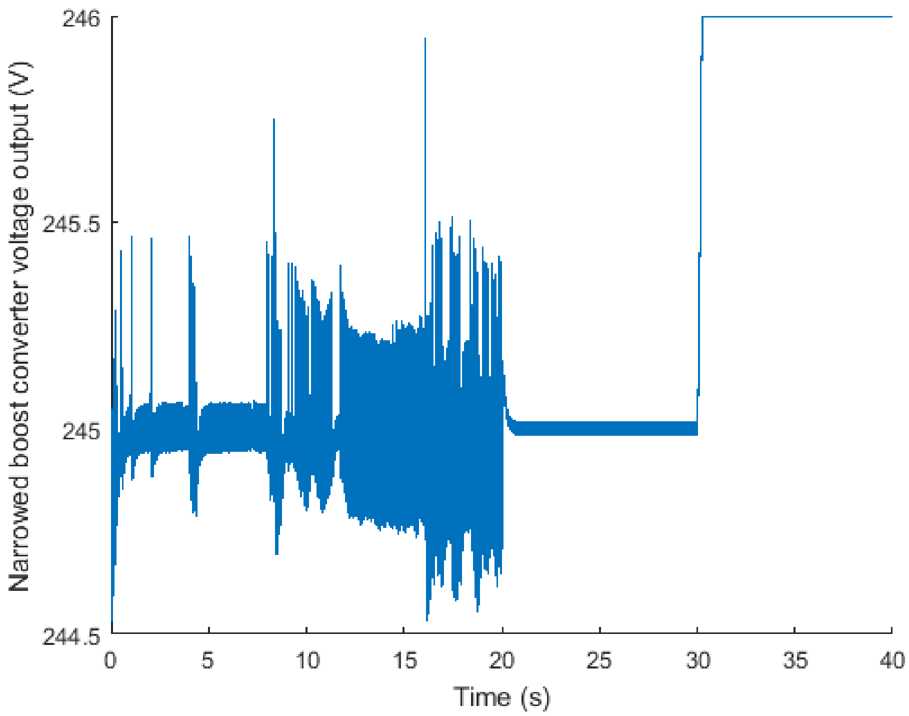


Figure 6.13: Output voltage from the boost converter throughout the full driving cycle

When it comes to the boost converter behaviour (figure 6.13), several stages can be easily spotted as well. Regarding the acceleration process, response time of the boost converter is fast and in addition voltage signal is mildly stable in between an acceptable voltage range. The signal stays at all times in between 244.5 and 246 V and, taking in account that the boost controller sets voltage output reference at 245 V, the signal must be considered as stable enough.

Nevertheless, as time keeps running in the simulation and speed and current are increasing, voltage keeps decreasing as stated in figure 6.5, where for a linear increasing change in load current voltage in the fuel cell decreases. As voltage in the fuel cell decreases it is harder for the controller to boost and maintain the output voltage at the set reference and for that reason higher distortion in the signal can be appreciated in acceleration stage for higher currents.

Once we enter in the constant speed stage, we can see how the boost controller has no problem whatsoever controlling the output voltage. It can be even seen how at the beginning of this second stage of the driving cycle, the output voltage follows a first order signal, as it should theoretically be. Regarding the deceleration process, voltage output suddenly rises, and the controller is not able to fully maintain voltage within the given reference. However, for purposes of the good performance of the whole system, signal is narrowed down between 244 and 246V, as said in section 6.2.

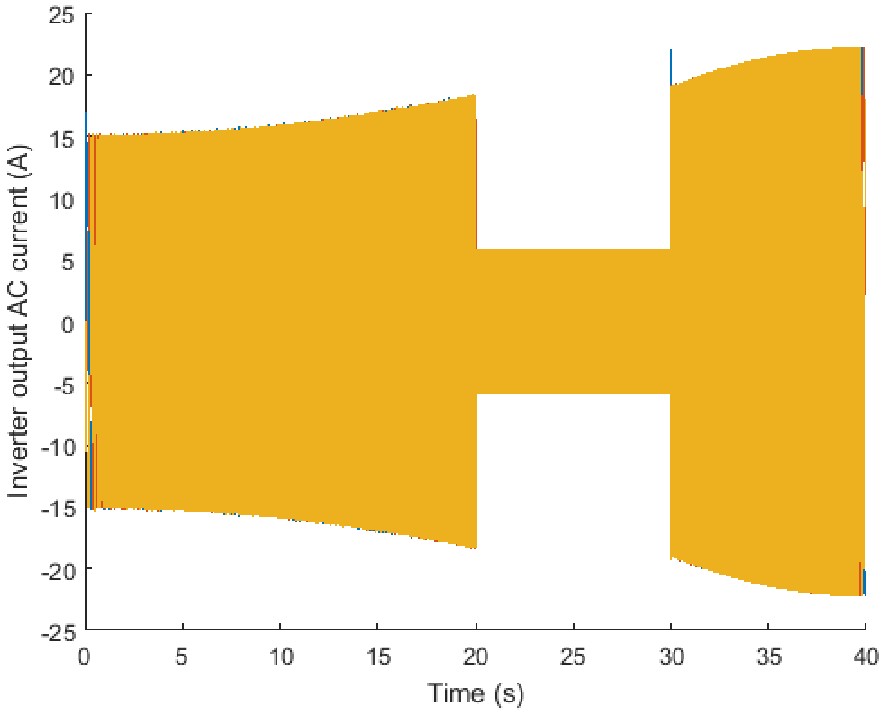


Figure 6.14: Inverter current throughout the full driving cycle

Figure 6.14 shows clearly what it has been stated above in previous explanations. In the acceleration stage we can see how current keeps increasing as we keep increasing speed. Current tendency could be described as semi-linear which is in fact the tendency that follows the power output from the fuel cell stack in this same stage of the driving cycle.

It can also be seen that for the second stage of the process, as it has been said earlier current needed is lower than in initial stages, as the system has just to maintain speed.

For the last stage of the process, in deceleration, current actually rises in absolute value (in module), but as it has been said earlier on, it is negative (reason why the motor is actuating like a generator). Anyway, current output in the inverter is three-phase alternate current which means that in fact module is the only important matter regarding output current, as argument is constantly changing. It is just after the motor that current is transformed again into DC current in order to feed it back to the fuel cell stack.

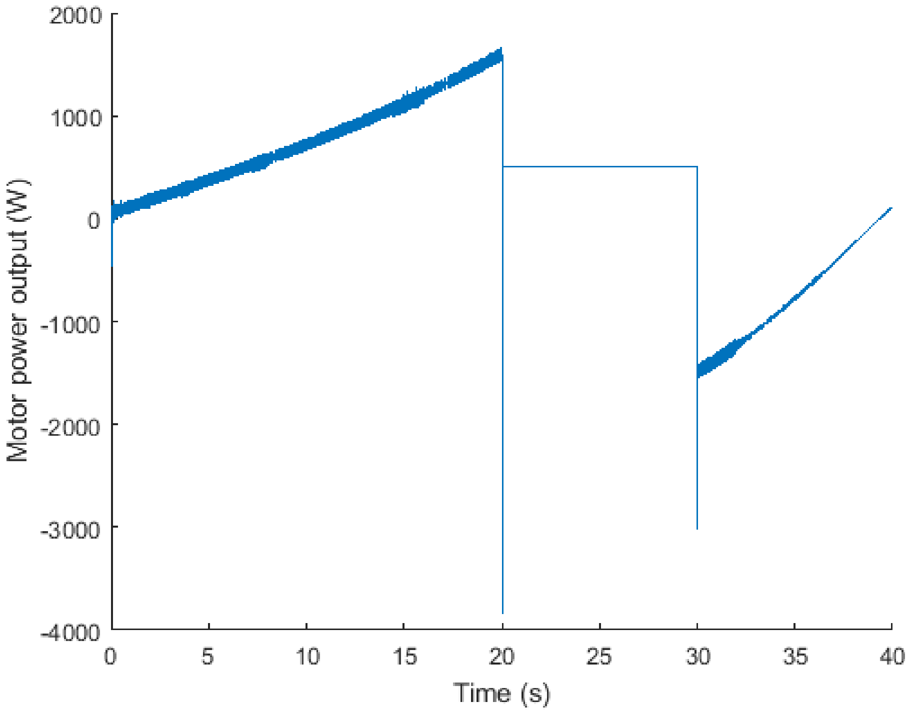


Figure 6.15: Motor power output throughout the full driving cycle

When it comes to the behaviour of the electric motor, we can see again in figure 6.15 three different types of behaviour regarding the three different phases of the inputted driving cycle. Just as the fuel cell stack, in the two first stages of the driving cycle power developed by the electric motor is very much similar in terms of both tendency and overall numbers. However, in deceleration the motor behaves like a generator. In this figure power appears as negative, which actually means that this motor in this stage of the driving cycle is generating power. This power could be used to charge the auxiliary battery of the system in which is called energy recuperation. Most of BEVs, plug-in hybrid and mild hybrid cars now in market already integrate this kind of technology, as well as FCV vehicles.

In all, it can be seen that the diverse elements in the system behave within what it is to expect of a system with this characteristics when submitted to an input of this nature.

7
Future Work

In the making of this project, it is clear that are several points that can be further developed and studied in a deeper way. In that way, there are several points that can be taken into account such as listed below:

- First and foremost, the most important point to try to improve would be the total power of the system. The system now conceived is an automotive vehicle of two kW of overall power which is equivalent to a small electric vehicle, capable to reach medium speeds. We would be talking of a city transportation vehicle. However, it is clear that a major improvement goes through increasing the total power that the fuel cell stack is delivering. Commercial car models have nominal fuel cell stack powers which go in ranges from 100 to 110 kW. Obviously, increasing the fuel cell stack power means that all other systems in the vehicle have to be adapted to this new power. The modelling of the electric motor would happen to have different modelling parameters and this eventually affects the DC/AC converter and the speed and torque control. It could also be probable that the boost converter elements (duty cycle, inductance and capacitor values) had to be recalculated in order to fit the voltage output of the fuel cell to the 600V to which high voltage systems are working.

  The only empirical data found for a fuel cell model was made for a 48 cell 500W fuel cell stack. In order to adapt it to a 2kW fuel cell stack the easiest solution was implementing a higher number of fuel cells in series. Nevertheless, adapting it to a 100 kW fuel cell stack using this method would not be feasible, as the voltage range would be way too wide and the number of cells would be impossible to assemble. For that reason, the whole set of empirical constants would have to be replaced in order to obtain proper ones, and the only way to obtain those values would be through testing, which was not conceived in the aims of this thesis.

  However, regarding the power increase for the fuel cell stack, once the set of empirical parameters for the 100 kW fuel cell stack is obtained, one could simply substitute the values in the Simulink model, as this model has been created in a totally generic way in order to tackle this issue.

  Once the fuel cell model is converted to a higher power output all the other elements can be easily adapted, as well as the data for the dynamic model of the vehicle (weight, wheel radius, drag and rolling coefficient, etc.) in order to get power results for a commercial fuel cell vehicle.

- Another point regarding the electric system would be the battery. While decelerating, all power from the motor shall be recuperated via regenerative braking, and then the auxiliary system battery should be charged in order to feed the low voltage systems during the start-up, as well as starting the power systems and put them to work. The battery could even be used to supply the vehicle with a power boost when needed.

  For that, a power control unit should be implemented. A device capable of choosing either energy recuperation should be activated or not, and capable of choosing which power power supplies to use in every situation possible. In that way, that device could decide whether to subtract power from the fuel cell stack, the battery or both. Of course it should also allow the battery to charge when decelerating, as said before.

- Regarding the electrical system, it is clear that exists several component setups and ways in which the power supplies could work together. In that way, a good point to look into further study would be how to optimize the configuration between the main power supply (the fuel cell stack) and the auxiliary power supply. This auxiliary power supply which normally comes in form of a battery, could even be something different such as super capacitors. Analysing the efficiency of the power supply elements, should be able to grant the possibility of choosing the optimal solution regarding multiple factors.

  For example, one could try to achieve the most cost-efficient solution, as the fuel cell stack is a very expensive part of a fuel cell vehicle. One could dimension the size of the stack trying to obtain the same power combining it with a bigger battery or super capacitors. In the same way, the system could be analysed and dimensioned in order to work with the maximum possible efficiency at all times. Taking in account the power the motor is requiring and the power that the fuel cell stack and the battery is supplying, efficiency curves can be made and then assess at what load currents those should work.

- Last, a good improvement would be to make a more detailed and complete vehicle model. The model at study is simply the electrical drivetrain, and the forces that actuate in the virtual vehicle in order to take angular speed and torque as a reference. However, one could implement a complete structure including a more detailed model regarding all mechanic systems and mechanic forces such as slip ratio in the tires, actual gearbox designing, etc.

8
Conclusion

After having done the study and the subsequent report, some conclusions can be extracted regarding both literature work and the modelling of the fuel cell vehicle.

Regarding the literature work on hydrogen and fuel cell technologies, several points can be stated, as follows below:

- Production of hydrogen is far from being a renewable process, as more than 90% of hydrogen production comes from fossil fuel consumption. Nevertheless, substituting fossil fuels for hydrogen as a power supply for energy systems would imply a major reduction regarding pollution into the atmosphere. Moreover, several options are appearing as mid-term and long-term solutions to even substitute conventional hydrogen procurement methods, that will eventually make hydrogen production, transportation and storage a greenhouse gas free, a totally green and environmentally friendly process.
- Regarding fuel cell technologies, it is clear enough that proton exchange membrane fuel cells is the fuel cell technology offering better performance when it comes to applying those to the automotive sector. Other technologies might be better when it comes to stationary energy procurement purposes. Nevertheless, proton exchange membrane fuel cells still have a long way in terms of material improvement and cost. The major breakthrough in this type of technology will come when manufacturing is cheap enough to compete with conventional modes of transportation, as other characteristics have been already matched, such as autonomy range and recharge time.
- It is clear enough as well that fuel cell vehicles cannot be commercialised in a full scale currently, because there is not a well implemented hydrogen transportation network with which fuel cell vehicle users can rely on in order to recharge their vehicles. This is without a doubt one of the major drawbacks that is slowing fuel cell vehicle acceptance down.
- Regarding the Simulink model, it can be seen that the results of the overall system are coherent and that the system responds as it should in the proposed situation. The fuel cell stack is able to deliver the range of power for which it was conceived and the power conditioning elements are able to adapt and control this power in order to give the electric motor the power to move the vehicle to the desired speed. It goes without saying that as commented in chapter 7, much improvement can be done in order to perfect this model.

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A

Appendix 1

A.1 Model Figures

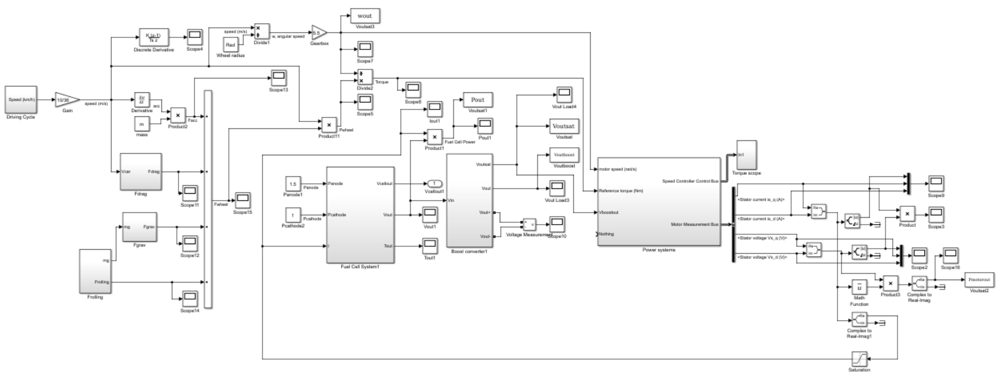

Figure A.1: Resultant model of the drivetrain of the fuel cell vehicle

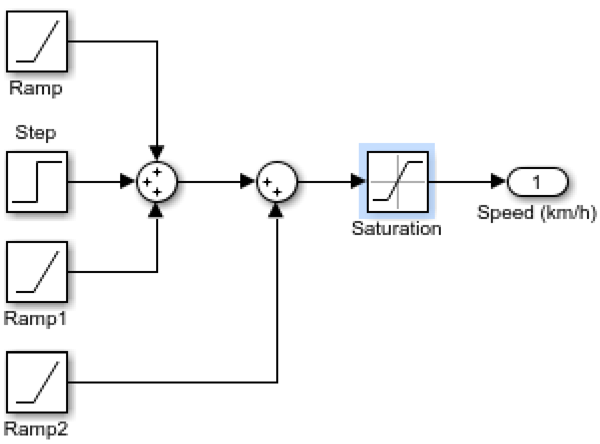

Figure A.2: Simulink implementation of the testing driving cycle

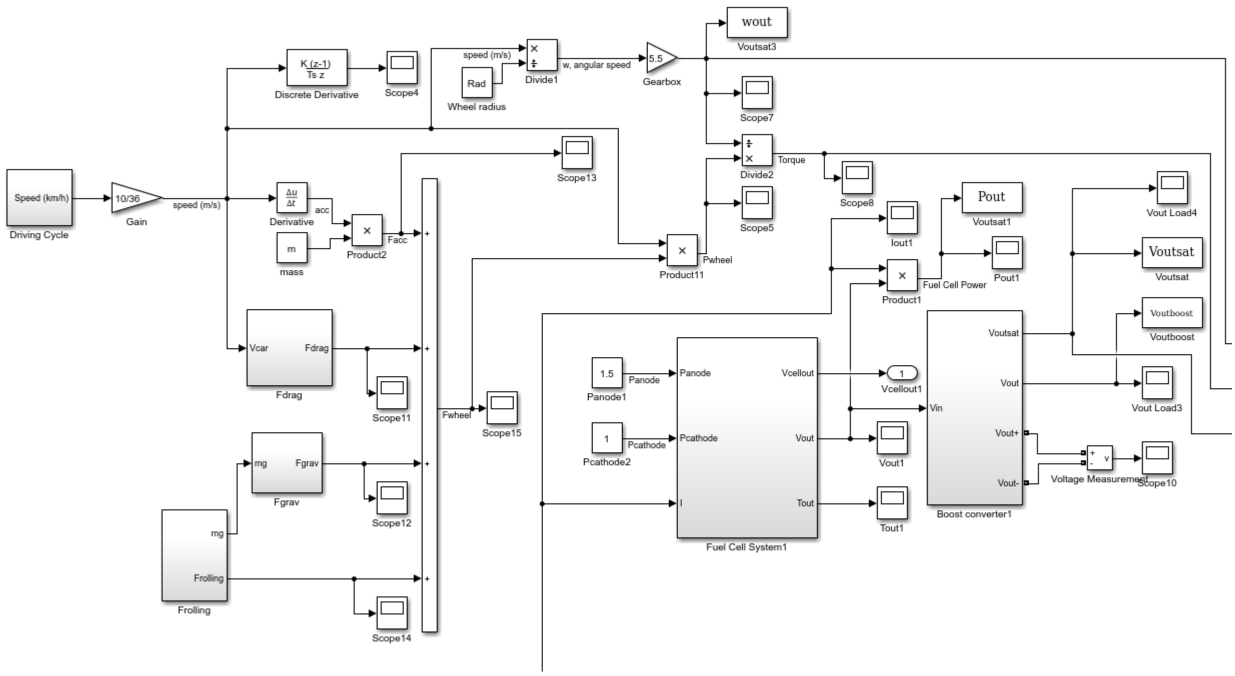

Figure A.3: Detail of force calculation, as well as PEFC and boost converter implementation

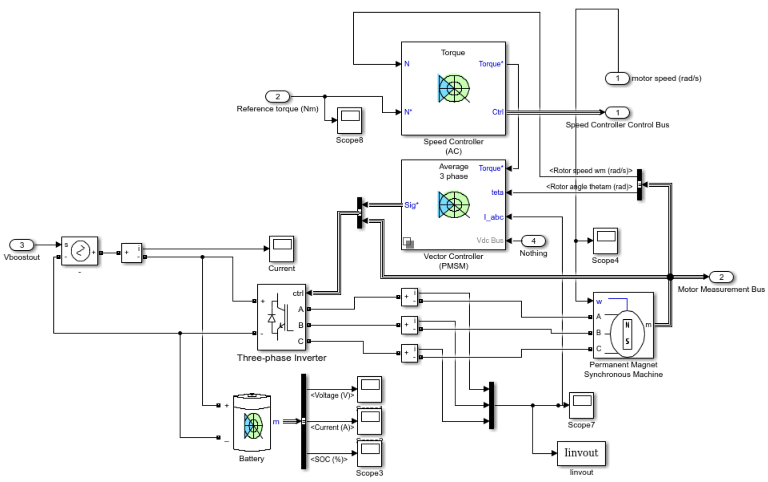

Figure A.4: Display of the power systems of the model

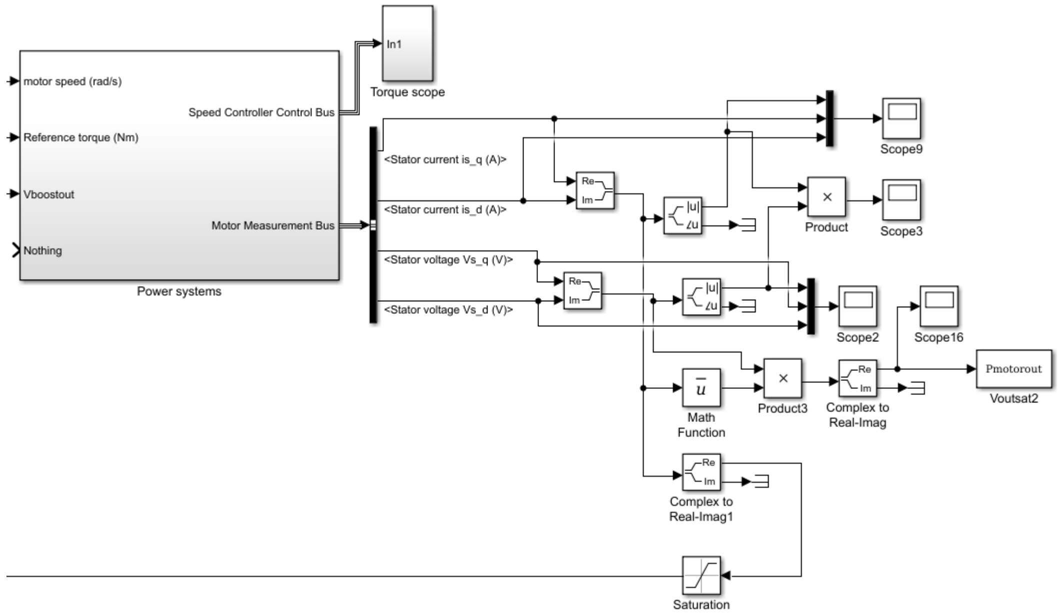

Figure A.5: Power calculations in the FCV model

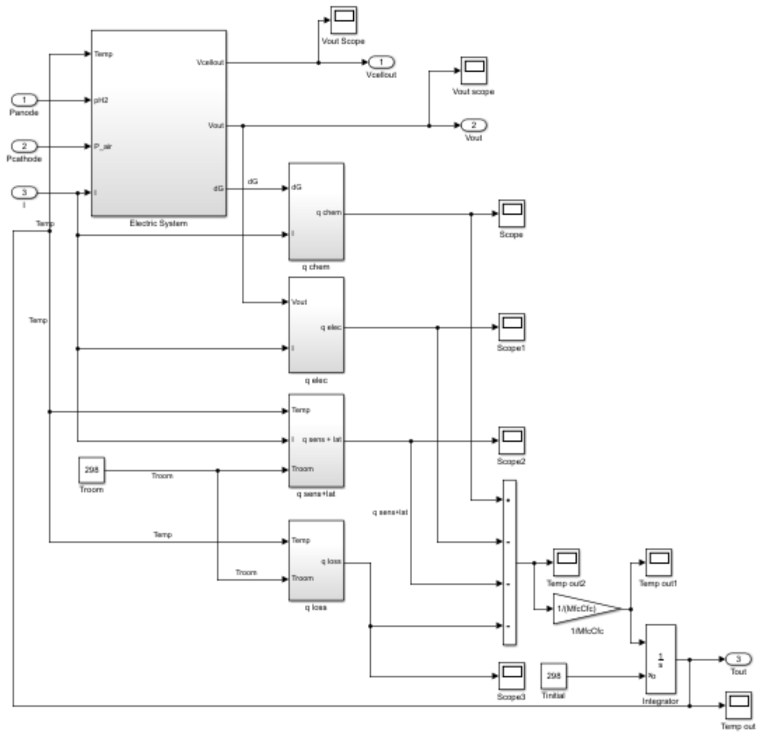

Figure A.6: Thermal structure of the PEMFC stack

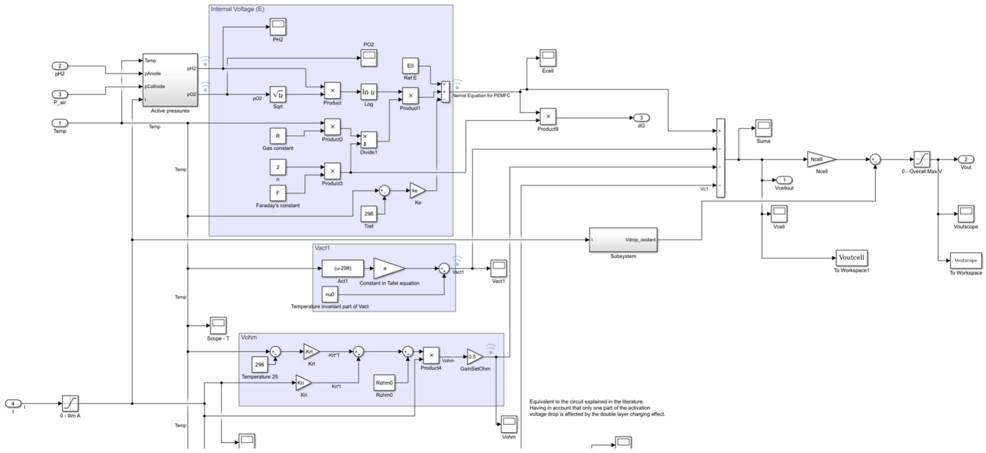

Figure A.7: Part of the electrical structure of the PEMFC stack

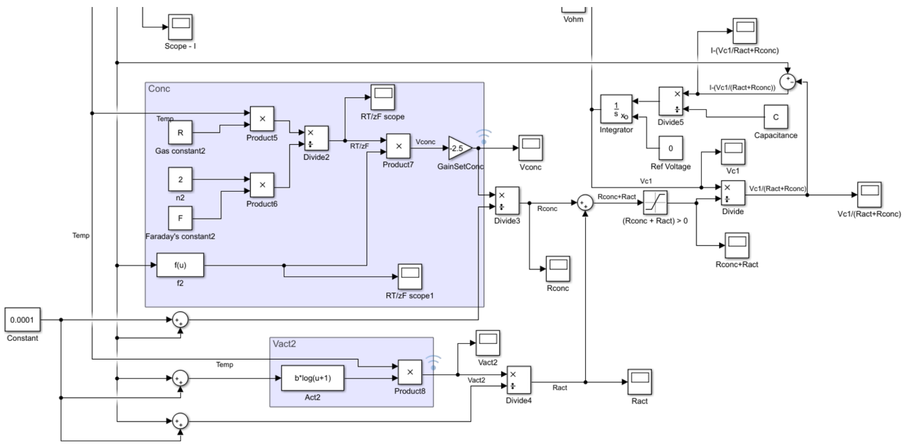

Figure A.8: Part of the electrical structure of the PEMFC stack

A.2 MATLAB/Simulink Simulation startup script

```
%VARIABLE DEFINITION

R = 8.314;
F = 96487;
Ncell = 180;
E0 = 1.227;
MaxV = E0*Ncell;
ke = 0.00085;
a = -0.00286;
nu0 = 0.419;
Krt = -0.0000494;
Kri = 0.000039;
```

```
Rohm0 = 0.00581;
Ilim = 25;
b = 0.000187;
C = 4.8;
Kdrop = 0.1584;
CpH2 = 28.68;
CpO2 = 29.39;
CpH2O = 75.4;
HvH2O = 40644;
Acell = 0.0032;
hcell = 37.5;
MfcCfc = 22000;
Ts = 2e-6;
m = 250;
Vwind = 0;
Af = 1.8;
rho_air = 1.225;
Cd = 0.27;
slope = 0;
Cr = 0.012;
alpha = 0.1;
g = 9.81;
Rad = 0.2;

%SIMULATION PLOTS

load_system('PEMFC_TOTAL_DYNAMIC');
sim('PEMFC_TOTAL_DYNAMIC');

figure;
hold on;
plot(Voutboost);
xlabel('Time (s)');
ylabel('Output Voltage (V)');

figure;
hold on;
plot(Iinvout);
xlabel('Time (s)');
ylabel('Inverter output AC current (A)');

figure;
hold on;
plot(Voutsat);
xlabel('Time (s)');
ylabel('Narrowed boost converter voltage output(V)');
```

```
figure;
hold on;
plot(Pout);
xlabel('Time (s)');
ylabel('Fuel Cell power output (W)');

figure;
hold on;
plot(Pmotorout);
xlabel('Time (s)');
ylabel('Motor power output (W)');

figure;
hold on;
plot(wout);
xlabel('Time (s)');
ylabel('Motor angular speed (rad/s)');

figure;
hold on;
e=(Pmotorout/Pout)*100;
plot(e);
xlabel('Time (s)');
ylabel('Powertrain overall efficiency (\%)');
```