DESIGN OF FUEL CELL POWER SYSTEM BASED ON UNMANNED UNDERWATER VEHICLE

A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES
OF
NEAR EAST UNIVERSITY

By
GÜNER ÜRÜN

In Partial Fulfillment of the Requirements for the Degree of Master of Science
in
Electrical and Electronic Engineering

NICOSIA,2018

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Approval of Director of Graduate School of Applied Sciences

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ABSTRACT

In the recent years, several factors such as population growth, technological development and industrialization have been caused to increase world energy consumption. Along to the increase of the needed amount of energy, the reserves of fossil energy sources have a great decline. Some gasses such as carbon dioxide, carbon monoxide, methane which are released by the combustion of fossil fuels cause a large part of the peripheral issues like pollution, overpopulation and climate changes. Because of this, in the place of using fossil fuels which cause the damage to environment and the decrease in their reserves, it is preferred to use environmentally renewable power resources. These are solar energy, wind energy, hydro power, fuel cells and hydrogen the main types of renewable energy sources. A great deal of research work in all developed and developing countries is about renewable energy sources. Unmanned underwater vehicles are filled in charge stations of batteries. The power of the stations is provided by the network.

In this thesis study, a power electronic circuit designed to provide a constant voltage to operate the unmanned underwater vehicle with the fuel cell. In this context, a DC/DC converter has been developed that converts the voltage of the fuel cell at 4.5 kW to the required tension. Since the fuel cell tension less than the required tension to operate unmanned underwater vehicle, for this reason boost type of converter is selected. The developed fuel cell and power circuit are designed in Matlab/Simulink computer environment.

Keywords: Renewable energy sources; unmanned underwater vehicles; fuel cell; battery; matlab/simulink

ÖZET

Son yıllarda nüfus artışı, teknolojik gelişme ve sanayileşme gibi faktörler dünya enerji tüketimini artırmaktadır. İhtiyaç duyulan enerji miktarının artmasının yanı sıra fosil enerji kaynaklarındaki rezervlerde çok büyük düşüş yaşanmaktadır. Küresel ısınma, hava kirliliği, iklim değişikliği gibi çevre sorunlarının büyük bir kısmının nedeni fosil yakıtlarının yanması ile açığa çıkan karbondioksit, karbonmonoksit, metan gibi gazlardır. Bu yüzden günümüzde çevreye verdiği zarar ve rezervlerdeki azalmadan dolayı fosil yakıtlar yerine çevre ile dost yenilenebilir enerji kaynaklarının kullanımı tercih edilmektedir. Güneş enerjisi, rüzgar enerjisi, su gücü, yakıt pilleri ve hidrojen enerji kaynakları başlıca yenilenebilir enerji kaynakları çeşitidir. Gelişmiş ve gelişmekte olan tüm ülkelerdeki araştırma çalışmalarının büyük bir kısmı bu kaynaklar hakkındadır. İnsansız su altı araçlarının sahip olduğu bataryaların şarjı şarj istasyonlarında doldurulmaktadır. İstasyonların gücü ise şebekeden saglanmaktadır.

Bu tez çalışmasında, insansız su altı aracının yakıt pili ile çalışabilmesi için sabit gerilim veren bir güç elektroniği devresi tasarlanmıştır. Bu kapsamda, 4.5 kW gücündeki yakıt pilinin gerilimini ihtiyaç duyulan gerilime dönüştüren bir DA/DA dönüştürücü geliştirilmiştir. Yakıt pilinin gerilimi insansız su altı aracının çalışabilmesi için gerekli olan gerilimden düşük olduğu için kullanılacak olan dönüştürücü türü yükselten olarak seçilmiştir. Geliştirilen yakıt pili ile güç devresi Matlab/Simulinkte bilgisayar ortamında tasarımı yapılmıştır.

Anahtar Kelimeler: Yenilenebilir enerji kaynakları; insansız sualtı aracı; yakıt pili; batarya; matlab/simulink

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LIST OF ABBREVIATIONS

AFC: Alkaline Fuel Cell

AUV: Autonomous Underwater Vehicle

C: Capacitance

CURV: Controlled Underwater Recovery Vehicle

D: Duty cycle

DC: Direct Current

Dmax: Maximum Duty cycle

DMFC: Direct Methanol Fuel Cell

Dmin: Minimum Duty cycle

EV: Electrical Vehicle

FC: Fuel Cell

fsw: Switching frequency

IL: Inductor current

Imax: Maximum inductor current

Imin: Minimum inductor current

Isw: Maximum switching current

L: Inductor

MCFC: Moltem Carbonate Fuel Cell

PAFC: Phosphoric Acid Fuel Cell

PEMFC: Proton Exchange Membrane Fuel Cell

Pmax: Maximum output power

PUV: Programmed Underwater Vehicle

R: Resistor

ROV: Remore Operating Vehicle

SOFC: Solid Oxide Fuel Cell

T: Period

UUV: Unmanned Underwater Vehicle

Vimax: Maximum input voltage

Vin, Vs: Input voltage

Vo: Output Voltage

Vref: Reference voltage

Vsmax: Maximum switching voltage

ΔI: Current ripple

ΔV: Voltage ripple

CHAPTER 1
INTRODUCTION

1.1 Thesis Overview

In the past years, the problems of energy dearth and the increasing environmental problems such as global climate change and air pollution makes important renewable and clean energy sources. The research of alternative power resources for power producing produce in solar power, fuel cell and etc. FC technology which is the subject of the alternative sources for electric power has been increasing interest (Nehrir et al, 2011).

Fuel cell is a hot prospect for the future topic of renewable energy which makes a commitment many advantages such as high efficiency and power density, the absence of burning, silent technology and having the ability that can be stored anywhere. One of the kinds of FC is Proton Exchange Membrane Fuel Cells (PEMFCs) which works short start-up time and low temperature condition (Larminie and Dicks, 2003).

Autonomous Underwater Vehicle (AUV) which is UUV can be achieved several self determination. The main prevalently used screening of deep ambience, obtaining waves, currents, depth, pressure and undersea information storage (Lee and Robert, 2004).

The main primary goal of this technology consideration is to provide an preliminary evaluation and technology viewing for the application of a PEMFCs energy method, operating on hydrogen and oxygen, to the propulsion of an autonomous Underwater Vehicles (AUVs). Currently secondary battery which is lithium-ion battery and in a few situations semi aluminum FC is exploited at the standard power system in autonomous underwater vehicles (AUVs). Secondary battery which is lithium-ion battery are easy and cheap resolution, and procure adequate energy to new practices (Szymak and Grzeczka, 2009).

Nevertheless, restricted power volume that far better restricts its self determination and mission suffers them. Unlike batteries, Fuel cell can stock its reactants exterior of mould and having close power like reactant could be stocked.

Consequently, FC has larger significant power than battery, it's illustrated, moreover while getting in consideration weightiness from parts like storing deposits.

Although profits that could procure, present autonomous underwater vehicles supported by a FC system, or a hybrid FC system aren't commercial. Therefore, this technology is even so necessary supporting progress also having an important relation with money (Belmonte et al, 2016).

There have been many concepts, prototypes and designs which are discussed in this thesis.

Today's analysis about the reviewing hydrogen and oxygen storing system and power intensity is given fairly comparison among the power system of FC and battery for autonomous underwater vehicles.

The PEMFCs which are the one type of FC emphasizes more because for autonomous underwater vehicle (AUVs). The proton exchange membrane fuel cells show better performance. Comparing other types, solid oxide fuel cell (SOFC) need high warmth, direct methanol fuel cell (DMFC) has less energy, pure gasses required for performing alkaline fuel cells therefore they are not enhanced to trade, and molten carbonate fuel cell (MCFC) and the phosphoric acid fuel cell (PAFC) cannot compress adequate. The whole system progress content PEMFC stack, step up boost converter (Swider et al, 2002). This thesis focuses on designing and simulating about the PEMFC based system without using battery on MATLAB/Simulink. Likewise model of boost converter is also modeled on MATLAB/Simulink. PI controller is used for converter controller.

CHAPTER 2

STATE OF THE ART LITERATURE REVIEW ON ENERGY SYSTEMS OF AUV

2.1. Introduction on Energy Systems of AUV

Urashima is a predatory autonomous underwater vehicle that uses PEMFC and Li-ion batteries like subsidiary energy resource. Towards the end of 1990, this system was begun to be improved by Marine Technology and Science Company in Japan. The developed autonomous underwater vehicle has a weight of about 10.5 ton, a length of 10 meter and a diameter of 1.5 meter. Urashima can travel around 305 km. Also it has capable of landing at a water depth of approximately 3600 meter. The voltage of the fuel cell with an energy system of about 2 kW is 120 volts. and Mitsubishi Heavy Company in Japan (Yamamoto et al, 2004).

The Urashima underwater vehicle that is the section of the hybrid system, uses a 36 Ah Li-ion cell because the fuel battery couldn't fail to provide the highest energy requirement. System notation includes FC deposits, moisturizer, temperature interchanger, water reservoir effect, fuel deposits and oxygen deposits (Sawa et al, 2005).

It has independent oxygen deposit from the Urashima system. Metal hydride liberates hydrogen via using the temperature transmitted from the reservoir by way of the water. At the beginning of the 2000 s, a marine experiment was carried out using a fuel cell with a travel time of 22 km for 6 hours. In 2005, a transit of 230 km 45 hours was carried out four times between transponders. At the end of 2005, there is an independent travel of 320 km for 60 hours was carried out at a water depth of about 850 meter and mean velocity of 1.55 m/s. Experts on this subject have specified some problems about the energy system of the Urashima underwater vehicle. They are still working to resolve these problems. Problems that need to be solved are the slow run time, the significant amount of hydrogen escaping, and the huge size of the system (Ishibashi et al, 2004).

The second generation autonomous under water vehicle improved from the JAMSTEC company in the near future. The underwater vehicle, which experts think is about to design, should be about 610 hours in durability, 3200 km in distance, 10,5 kW power and 5500 kW in total capacity. Thanks to computer software, PEMFC prototype is designed for autonomous underwater fuel cell power system. This system provides high efficiency.

The new method that differentiates and improves the structure of the fuel system and the working principle. This is done by sullying the period blowers and changing place with valves. In 2009 a new model was tested in the computer environment to improve the material and MEA composition and to remove the humidifiers by reducing hydrogen leakage. With over 1000 hours working time, 55% percentage working efficiency was achieved.

Towards the beginning of 2011, the prototype of the FC system comprised of two 160 kW fuel deposits, an electronics control system, and a compression tank. Until the beginning of 2011, 600 hours of perpetual energy was provided. In 2011, a successfully electricity generation was achieved by prototype during the sea testing. JAMSTEC's "Deep Draw" research topic was successfully established in FC system in 2013. The installed system was immersed 180 m deep and powered two units of investigation instruments. Experts indicate that the requested power is provided in a certain way and that the supplied products can run continuously (Yoshida et al, 2011).

DeepC autonomous underwater vehicle is an experimental project improved by STN ATLAS electronics company for German. The Deepc autonomous underwater vehicle is financed by the German Ministry of Education and Research. Characteristics of the autonomous underwater vehicle to be developed, it is necessary to have a speed of 2.5 m/s (5 knots), working time of about 65 hours and a downward distance of 4 km from sea level. There are three connected boats in the vehicle, two similar drive boats and one cargo carrying capacity.

The energy system of the DeepC autonomous underwater vehicle consists of a hybrid battery-PEM fuel cell, as well as an additional battery that holds sudden high loads. The fuel cell has a total of 60 cells and has a power of 3.5 kW.

Fuel the oxygen required for the operation of the battery is stored at 350 bar pressure depot and necessary hydrogen at 250 bar pressure depot. Stored oxygen and hydrogen produced a power of 145 kWh (Hornfeld, 2004).

It is an underwater vehicle created by integrating a PEM fuel cell into a present autonomous underwater vehicle. The IDEF has a weight of approximately 1.5 ton and lengths around 7 meters. The integrated PEMFC is modeled by HELLION company. The PEMFC deposits consists of 64 cells and generates 1.6 kW of power. The average efficiency of the system is around 50 percent considering the wastes. The reactant recycles oxygen and hydrogen gases to provide transformation. System can be placed at aluminum pressurized container that is pressurized via nitrogen to preserve gas leakage and volatile gas mixes. The type of IDEF AUV, which was filled with gas 8 times in 2009, has a travel rate of 300 km and a depth of 450 meter (Raugel et al, 2010).

2.2. Conceptual Designs

It is designed to improve the productivity of resident trading gliders, involving durability, nominal energy degree which bases modeled after a university study. The structure could be approximately 75 kg in weight, length of 2.4 meter, caliber of 23 cm and 6400 cm3 proton exchange membrane fuel cell volume. A study was conducted to calculate the productivity and applicability of the proton exchange membrane fuel cell system by using 12 volts 90 watt power. The designed structure owns Nafion lamina of 33 cm2 . There are 2 hydrogen and 2 oxygen deposits in the system. This system does not still have a model (Wu et al, 2009).

A Practical Search Laboratory in America, researches examine the use of fuel pellets, especially for autonomous underwater vehicles and submarine drive applications. They have been studying on a PEMFC with a power of 450 Watts in the energy systems partition of the search and implementation laboratory. This laboratory, which has a large battery-powered AUV called Seahorse that can be converted into a fuel cell operation, has never implemented a fuel cell system in submarine (Davies et al, 2006).

The Naval search center is an office for the United States Naval Agency which is looking for submarine science and technology programs. The improvement of unmanned underwater vehicles has been closely followed and participated since the beginning.

They are particularly interested in designing and modeling huge autonomous underwater vehicle. Because of this, they could be also funded in the improvement of FC energy systems for autonomous underwater vehicles. In four year term, the total amount was about 17 million dollars. The projects are planned to be improved then three stage plan. In recommended system, they also set a few objective criteria for the energy system to be established at the same time. These measurements contained an energy intensity requirement of 25 W/L, a max length around 76.5 cm power dissipation, an energy content of 70 kWh, and a durability above 35 hours (Davies et al, 2006).

CHAPTER 3
UNDERWATER VEHICLES

3.1 Introduction to Underwater Vehicles

Underwater surveys; today, it is carried out in civil and military applications for various purposes such as protection and examination of natural and environmental resources, various construction activities, provision of coastal and country security. Much of the academic and industrial research done in the last two decades has been about the use of unmanned platforms in order to avoid the risk of human life.

The elements that makes the work difficult in this area;

- Lots of material wear due to salt and pressure effects under sea,
- To create a challenging environment due to the perturbation of wave movements in the sea,
- Seawater has very limited permeability within the electromagnetic spectrum and a certain degree of permeability (Lee et al, 2004).

This is why wireless autonomous design of vehicles that can operate underwater is a major strain for scientists, due to a number of physical facts, such as RF communication problems and the lack of energy storage required for the task. Because of some physical facts, the design of the tools that can work underwater is compelling for scientists, and on the other hand it is becoming more and more attractive. Indeed, each of the issues such as communication design, navigation, control and guidance solutions as well as hardware designs in the system solution of the respective vehicles are separate research topics. Unmanned underwater vehicles are used by researchers to provide simple, long-range, low-cost, fast response capabilities for collecting appropriate environmental data (Abreu et al, 2010).

3.2 Classification of Underwater Vehicles

Underwater vehicles can be classified as mainly human and unmanned systems, as can be seen in Figure 3.1 below.

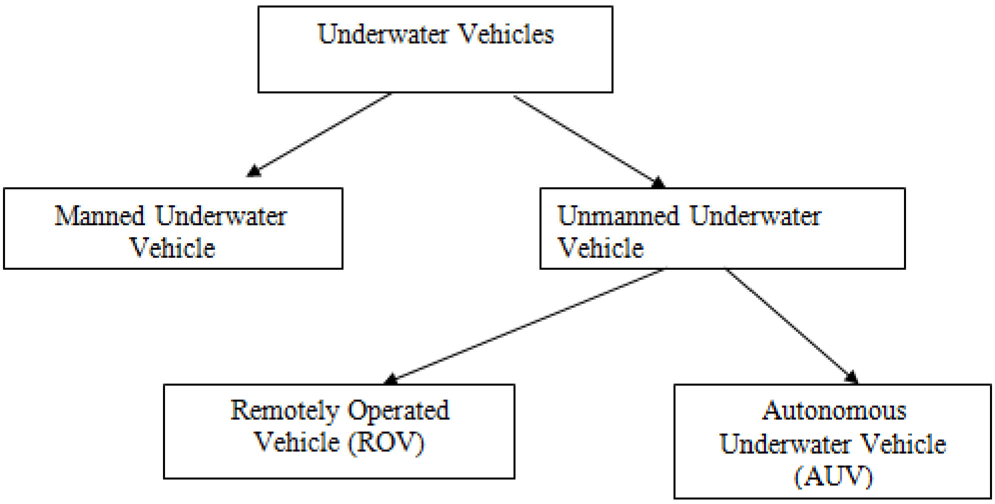

Figure 3.1: Basic classification of underwater vehicles (Griffiths, 1997)

3.3 Unmanned Underwater Vehicle

Unmanned underwater vehicles are vehicles that have utility loads (camera, sonar etc.) mounted on a waterproof structure with the ability to dive underwater and to move underwater, and transmit data to the elements on the surface, either wired or wirelessly. Unmanned Underwater Vehicles are basically evaluated in two main groups as Cable Controlled and Wireless-Autonomous. Cable-controlled "ROV (Remote Operating Vehicle)" and autonomously controlled "AUV (Autonomous Underwater Vehicle)". Under the most general definition, remote controlled underwater vehicles are underwater robots that perform a variety of functions that can be dangerous for different purposes underwater by being controlled remotely through an operator.

Therefore, a Remotely operated underwater vehicle system; besides the vehicle, the operator controlling the vehicle, the equipment the operator provides for this control, a cable connecting the vehicle to the surface, and crane assemblies that allow the vehicle to be lowered and removed from the water.

Remote controlled underwater vehicles can be relatively small and simple means of receiving images and measuring some of them by means of underwater cameras for monitoring purposes only in terms of size and function as well as being equipped with a large number of sensors (camera, sonar etc.). It can be in large systems that have a working competence and perform quite complicated functions using robot arms (manipulators). The tools that can be considered as business-class remote-controlled underwater vehicles, originally considered as unmanned underwater machines, are capable of carrying out very difficult construction and maintenance tasks at depths exceeding 3000 m by eliminating the limitations and hazards of human diving limited to 260 m.

The remote controlled underwater vehicles, which weight 3-15 kg and are called Micro/Mini ROV, offer an economical solution for working underwater corridors. Today's technology, which makes possible the design and use of AUVs, allows unmanned underwater vehicles to operate completely independently, harboring their own navigation systems and power units, without the many cable connections that cause problems and operational difficulties.

The most basic distinction of autonomous underwater vehicles from ROVs; AUVs are autonomous/semi-autonomous and can be summarized as having their own power sources. More importantly, autonomous underwater vehicles are designed and equipped so that they can perform their planned tasks in pre-planned routes, as well as in situations where they have not been foreseen during their duties according to their autonomy levels, or where there is no communication.

In general, AUVs are designed and manufactured in a cylinder-fish form in a hydrodynamic body. Water tanks used to dive in normal submarines are absent from these vehicles; in particular with autonomous underwater vehicles, instead of ballast tanks, it provides diving with engines and moving wings.

The main principle can be summarized as the device being light weight from water and in the event of any problem-failure, the self-falling water surface (Stevenson, 2002).

3.3.1 The usage area of unmanned underwater vehicle

Unmanned underwater vehicles are widely used today on the military and civilian areas.

In civilian area;

- Search and rescue
- Underwater pipe and cable laying and inspection
- Abutment controls
- Underwater situation awareness
- Underwater construction and maintenance / repair
- Underwater sampling
- Recover sunken
- Underwater and evidence extraction
- Environmental research, environmental pollution
- Oceanographic surveys, biodiversity studies
- Investigation of submerged objects such as ships, wrecks, aircrafts, etc.
- Underwater power stations, hydropower and power plants
- Examination of water reservoirs, dam covers and water sets
- Investigation of underwater pipeline welding
- Fish, crab and water surface investigations
- Zebra mussels and cleaning
- Archeology studies
- Underwater mapping and verification
- Documentary filming
- Water parks
- Corrosion and cathodic measurements
- Underwater crime scene investigation
- Examination of ship boat, propeller and guiding equipment
- Diving as a diving supervisor and support person

can be ordered (Abreu et al, 2010).

In Military field, it’s used for manipulator systems, underwater exploration and surveillance, port and critical area security, mine diagnosis, diagnosis and destruction, anti submarine warfare, fleet escorts, submarine rescue, and wreck operations.

Miniature vehicles are generally used for underwater exploration and observation operations and are used for any leakage, crack, fracture control under water, oil and pipelines. By the shipyards, "Are there any faults or algae under the ships?" It is also used in the examination of dam covers. The security units are used for corpses and evidence research activities. Scientists use these miniature tools for underwater sampling and observation. One of the places that is heavily used is the fish farms, which are very important to check if the farm nets are torn. It is necessary to regularly divert the diver every day. Instead of the diver, it is a serious alternative to use such products in bad, cold weather.

In particular, oceanographic solutions have become a subject of widespread concern in recent years, particularly due to the study of global warming effects; therefore, autonomous underwater vehicles constitute the largest percentage of applications (Inzartsev, 2006).

3.3.2 History of unmanned underwater vehicle

Although there is no acknowledgment of who developed the first unmanned underwater vehicle in history, the first of the two oldest recordings was a torpedo-shaped remote control, developed by Luppis-Whitehead Automobile in Austria in 1864 under the name PUV (Programmed Underwater Vehicle) underwater tool.

The first remote-controlled watercraft closer to the form that is common today is the Poodle named vehicle designed by Dimitri Rebikoff in 1953. The first serious advances in the development of unmanned underwater vehicles were undertaken by. These vehicles, which can be classified as remote controlled underwater vehicles without autonomic features, have been used for mine and explosive destruction and cleaning purposes in the first years.

The British Royal Navy has effectively used remote controlled underwater vehicles to clean training boats that have been underwater for a long time after the exercise.

The US Navy's Cable Controlled Underwater Recovery Vehicle (CURV), which took off the atomic bomb after a plane crash in Spain's Palomares township in 1966, rescued submarine crews sinking in Ireland in 1973 with only a few minutes of oxygen remaining, are the most important examples of how remote-controlled underwater vehicles can be useful for operational purposes (Nuno, 2011).

3.3.3 Current practices of unmanned underwater vehicles

With today's technology, it is also possible to design and use autonomous underwater vehicles that allow unmanned underwater vehicles to operate completely independently through their own navigational systems and power units. The main difference between autonomous underwater vehicles and remotely controlled underwater vehicles is that autonomous underwater vehicles are autonomous/semi-autonomous and have their own power sources. Autonomous underwater vehicles can function in pre-planned routes, and can even react to unforeseen situations during the mission, based on autonomy levels. Both remote controlled underwater vehicles and autonomous underwater vehicles can be used for commercial, military and academic purposes (Bocharov, 2009).

CHAPTER 4
BATTERIES

4.1 Batteries

The most basic element that makes up the battery is the electrochemical cell. A battery is formed by connecting some of these cells in series. Figure 4.1 illustrates the main operating principles of battery.

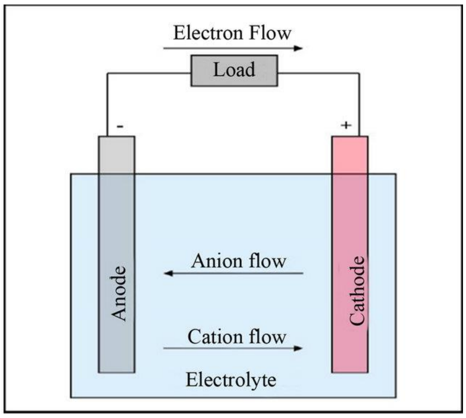

Figure 4.1: The basic working principal of electrochemical cell (Chen and Chau, 2001)

The anode and cathode electrodes of the battery can be separated from each other by an electrolyte. During the discharge event, to cathode electrode causes an oxidation reaction to lead the electrons to the outer circuit, whereas a reduction reaction occurs in the positive electrode. During charging, the electrons are released to generate the oxidation for the anode electrode, while electrons are injected to the negative electrode to form reduction. The most commonly used power storing devices to AUVs implementation will be explained in this chapter. Also it will be explained which kind of applications are more suitable. These batteries have been classified in the literature as lead acid-based, nickel-based, zinc/halogen, metal/air, sodium-beta and ambient temperature lithium batteries (Emadi, 2005).

4.1.1 Lead acid (Pb-acid) batteries

This battery, devised around 1860s, used as popular trading production to centuries. Lead-acid batteries are an old and widespread technology used in many applications. For main reason of the widespread use is simple technology and low price. Open circuit voltage of these batteries consist on concentration of acid. Also, it becomes free from lead, sulphate and dioxide present into cell. The advantages of this type of batteries are: simple technology, high cell voltage, to provide good performance for unmanned underwater vehicles, high operating and a wide range of sizes and designs. On the other hand, the lead-acid batteries have less significant power and power intensity than the others. This situation provides to have disadvantages of a higher spontaneous discharge time (1% per day at 25°C), lower usage lifetime (500 charge/discharge), electrode corrosion due to sulfur it also has disadvantages such as not being long-lived. To overcome these disadvantages, different technologies are being developed to provide a more efficient use in AUVs. VRLA is the one of them (Ceraolo, 2000).

4.1.2 Nickel based batteries

Many kind of batteries such as Nicel cadmium that use nickel oxyhydroxide like live product in cathode electrode. Among such batteries Nickel cadmium is better due to authenticated technology also successful productivity that is more suitable and widely accepted type for electric vehicles. In addition, Ni-MH type batteries are developing gradually and it is predicted that Ni-Cd batteries may take place in the coming years (Emadi, 2005).

4.1.3 Ni-Cd batteries

This kinds of batteries can be used in heavy industry long since. The nominal parameters of Ni-Cd batteries are 1.2 V, 56 Wh/kg, 110Wh/l also 230 Wh/kg. Like electrolytes, liquid alkaline can be used. The most importance thing such this batteries is due to their high specific gravity, high lifetime charge/discharge, mechanical and electrical operating under severe conditions, a constant tension profile against wide discharge current variation, very low spontaneous discharge characteristics. The disadvantages are high cost, low cell tension, and harm to the environment (Emadi, 2005).

4.1.4 Ni-Zn batteries

Because of using short-life zinc electrodes, these types of batteries are not as commercially viable. Due to the studies on increasing the life span, it is evaluated that it can gain importance in the after days because of high specific energy also less material price. Ni-Zn batteries have nominal 1.6 V, also other parameters are given at Table 4.1. In Ni-Zn batteries, zinc is used as a negative electrode, nickel oxyhydroxide is used as a positive electrode, in addition alkaline potassium hydroxide is used for electrolytic. Compared to other nickel-base batteries, it is suitable for operation with high specific energy and power, low project cost, no toxicity, high charge and discharge rates wide working hot spots. The main disadvantage is that the service life is short (Corrigan and Masias, 2010).

4.1.5 Ni-MH batteries

Its characteristics resemble with Nickel cadmium batteries. Primary differentiations among these are that such batteries hydrogen usage which is sucked into the metal instead of cadmium as the negative electrode. The absence of cadmium and the better specificity of Ni-Cd make these batteries superior to Ni-Cd batteries. The nominal operating parameters are specified as 1.2 V, 65 Wh/kg, 150 Wh/kg and 220 W/kg.

The metal hydride used in the battery allows the hydrogen to absorb and discharge hydrogen while charging and discharging the battery. The main component used as electrolyte is potassium hydroxide. The main advantages of this currently developing techniques can be briefed like having high significant power and power intensity, being environmentally friendly, having a flat discharge profile, and being quickly rechargeable. Its main disadvantages are high cost, memory effect and exothermic in case of charging (Chen and Chau, 2001).

4.1.6 Metal-air batteries

By connecting the reactive negative electrode with an air electrode, metal/air batteries are provided with an insoluble positive reactant electrode. These types of batteries have very great significant power and power intensity because it uses the air and many metals found in the environment. Due to this performance, much effort is being made to develop it.

Electrically and mechanically rechargeable versions have been developed. It has a flat discharge voltage and its capacity is independent of temperature and load (Gao et al, 2002).

4.1.7 Zn/air battery

Such a batteries have been developed both electrically and mechanically rechargeable. Despite being both competent, mechanical charging is preferred in electrical vehicle applications. Specific typical futures of Zn-air batteries are shown at Table 4.1. Zinc particles in cathode electrode and air electrodes in anode electrode are used (Elmadi, 2005).

4.1.8 Al/air battery

The most focused metal material in metal/air battery development work is aluminum because it is very common in nature, low cost and easy to use. The open cell voltage of this battery is 1.4 V. Aluminum is used to cathode electrode. Also, anode electrode, unifunctional air electrode can be used to operate during discharge. A salty solution is used as electrolyte. Salty electrolyte solution is only interesting in low power applications. Such batteries which are available using for power implementation parameters are given Table 4.1. However, significant power can be reduced to 6 W/kg for these batteries. It can not be used alone as a power source in electrical vehicle applications due to its extremely less significant power. It can be used in combination with another battery to increase the range of AUVs in order to exploit very more significant energy and energy intensity (Corrigan and Masias, 2010).

4.1.9 Zinc Sodium Sulfur battery

This type of battery works at a temperature of 300-250 degrees Celsius. Other working conditions and properties are illustrated at Table 4.1. However, according to battery configuration, these characteristic values may have a lower value. Melted natrium in cathode electrode, natrium polysulfide in anode electrode is used. Electrolyte of beta aluminum ceramics electrolyte forms reagent medium which will prevent direct discharge between the solid medium ion-conducting and molten electrodes.

Its main features are high specific power, high energy efficiency, flexible operation in changing working conditions at large values, and can work without being sensitive to environmental conditions. In addition, there are limitations and disadvantages that need to be developed, such as safety problems, the need for thermal regulation (Gao et al, 2002).

4.1.10 Na/NiCl2 battery

In this battery type live products can be melted natrium to cathode electrode also, solid nickel chloride about anode electrode. As used at Na/S batteries, beta aluminum ceramics electrolytes are additionally usage for natrium aluminum clotrite electrolyte. Operating temperature is 250-350 degrees Celsius and conventional cell tension can be around 2.5 Volts. Related parameters are shown at Table 4.1. Compared to Na/S, it has higher open circuit cell voltage. It can work in a wider temperature range. It is safer but the costs are too high (Chen and Chau, 2001).

4.1.11 Lithium-polymer batteries

Such batteries use lithium metal as the negative electrode and a transition metal (MyO2) that contains oxide as the positive electrode. MyO2 metal has a layered structure in which lithium ions can enter or discharge ions during charging/discharging. Basic properties like power intensity and significant power tensions are shown in Table 4.1. Having greater tension, more significant power and power intensity voltage, very less own-discharge ratio are main advantages of being able to be produced and secured in a wide range of sizes and shapes. In addition, poor performance at low temperatures due to ionic conduction is the main disadvantage (Emadi, 2005).

4.1.12 Lithium ion batteries

This type of battery has been rechargeable since it was first produced. Despite its continued development, electrical vehicle is widely accepted in its applications. Lithium ion batteries LixC uses lithium-carbonated carbon as cathode electrode also anode electrode uses lithiated transition metal excal-sation oxide (Li1-xMyOz). A solid polymer or a liquid organic solution is used for the electrolyte. During loading and discharge, Li-ions move among the anode and cathode electrodes in the electrolyte. The nickel-base Lithium ion batteries specifications are shown at Table 4.1.

Cobalt-base species show a high significant power and power intensity, but they also bring about a significant self-discharge rate and higher production costs. The mangan-base species have less price, and significant power and power intensity values have a value between species based on cobalt and nickel.

Consequently, these improvements about Li-Ion batteries, it can be thought oriented towards manganese-based species because it is very present in nature, environmentally friendly and most importantly low cost. The most important advantages of such batteries are that they have the highest value of open circuit cell voltage, high significant power, power intensity and the most secure modeling and having the talent for charging or discharging several batteries. However, such batteries have the disadvantage of having a spontaneous discharge rate of 10% per month (Gao et al, 2002).

4.2 Comparison of Batteries

Comparisons of various significant variables like significant power, power intensity, charge or discharge lifetime and cost which is described battery types are also shown in Table 4.1.

Table 4.1: Comparison of the batteries used in AUV compared to certain parameters (Chen and Chau, 2001)

Battery type	Specific energy (Wh / kg)	Energy density (Wh / l)	Specific power (W / Kg)	Charge/ discharge life cycle	Cost ($/ KWh)
VLRA	30-45	60-90	200-300	400-600	150
Ni-Cd	40-60	80-110	150-350	600-1200	300
Ni-Zn	60-65	120-130	150-300	300	100-300
Ni-MH	60-70	130-170	150-300	600-1200	200-350
Zn/Air	230	269	105	----------	90-120
Al/Air	190-250	190-200	7-16	----------	-----------
Na/S	100	150	200	800	250-450
Na/NiCl2	86	149	150	1000	230-350
Li-Polymer	155	220	315	600	-----------
Li-Ion	90-130	140-200	350-450	800-1200	> 200
USABC	200	300	400	1000	< 100

The values shown in Table 4.1 are for illustrative purposes only, as the data may vary for different manufacturers. Significant changes can be observed even between different models of the same manufacturer.

Table 4.2: Comparison of key features of AUV batteries (Chen and Chau, 2001)

Battery type	Advantages and Disadvantages of AUV Applications
VLRA	Mature technology, low cost, fast chargeability, high specific power/low specific energy
Ni-Cd	Mature technology, fast chargeability, high specific power/high cost, low specific energy
Ni-Zn	High specific energy, high specific energy, low cost, short life
Ni-MH	High specific energy, high specific power, fast chargeability, high cost
Zn/Air	Mechanically rechargeable, low cost, very high specific energy, can not use regenerative energy
Al/Air	Mechanically rechargeable, low cost, very high specific energy, can not use regenerative energy
Na/S	High specific energy, high specific power/high cost, safety issues, thermal regulation requirement
Na/NiCl2	High specific energy/high cost, heat regulation requirement
Li-Polymer	Very high specific energy, high specific power/poor low temperature performance
Li-Ion	Very high specific energy, very high specific power/high cost

Table 4.2 illustrates advantages and disadvantages about the batteries described above. VLRA and Nickel based batteries that can be likely used in foreseeable future and have a high likelihood. Because the properties of Ni-MH out of its immature technology, Nickel based batteries are superior that of Ni-Cd. In fact, some manufacturers who produce Nickel cadmium batteries for AUVs applications get attempted for producing Ni-MH batteries. Therefore, VRLA in the close vicinity will still be popular due to its mature technology and low cost, but Ni-MH is attractive due to its successful performance. On the other hand, Zn-Air, Ni-Zn, Na-NiCl2 and Lithium batteries have high potential in the mid-range.

Li-Ion batteries are seen by many manufacturers as the most important AUV battery in the mid-range.

The biggest disadvantage is that the cost of production is high. Zn/Air batteries are also important because of their high specific energies and mechanically fast chargeability.

However, they can’t accumulate regenerative energy because they can be mechanically charged. The main disadvantage of Ni-Zn batteries is that they are short-lived. Na/NiCl2 is an acceptable battery with higher temperature for AUV applications than others. If battery performance can be improved, there is hope in mid-range. Li-Polymer batteries are performing well in AUVs applications. If more battery makers increase their research for this battery, then a medium battery will be an important battery (Chen and Chau, 2001).

CHAPTER 5

CONVERTERS

5.1 DC/DC Converters

The fuel cell can be used as the main energy source in electrical vehicles applications, but the power density of the fuel cell is low. A battery storage unit must also be added to the system in order to maximize power in the transient case and to avoid problems caused by the fuel cell's dynamic response being too slow. With the aid of DC/DC converters, the output voltage of the fuel cell is converted to the input voltage required for the motor controller. One thing to consider for this process is that the cost of DC/DC converters is low and takes up little space in the vehicle.

The DC/DC converters are designed to be used as an interface for power electronics in EV applications, which is a very difficult task for some reasons. First of all, these converters have to work at high power and low voltage levels, so their currents can be hundreds of amps. High value currents don’t only increase the thermal and electrical stress on active and passive circuit elements, but also reduce the efficiency of the DC converter.

Secondly, since the input voltage varies over a wide range, this change will also increase the current or voltage on the active and passive components as it will change the ratio of the output voltage to the input voltage. Thirdly, due to the reasons mentioned above, converters also make it cost-effective and difficult to produce with a small footprint. It is better using DC/DC converters to support regenerative formations and power recovery operations in AUV applications (Marei et al, 2003).

5.2 Boost Converters

Figure 5.1 shows the simple structure of a boost DC/DC converter circuit that is often used with renewable energy sources.

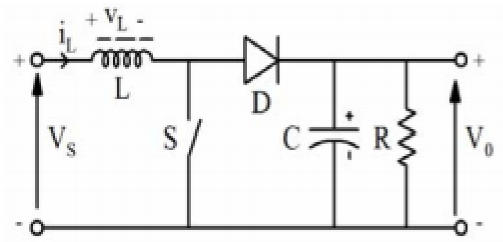

Figure 5.1: Boost type dc-dc converter structure (Agrawal, 2001)

The control mechanism shown in Figure 5.1 is implemented according to the transmission and cutting state of the semiconductor power switch. When the switch is at transmission state, the current through the coil increases and energy starts to be stored on the coil. When the switch is at cutting state, the charge current passing through the coil starts to flow through the diode D to the capacitor C and to the load. The coil discharges its energy and the polarity of the voltage on the coil is the same as the polarity of the voltage source. And it is connected to the load via diode D. Therefore, the level of the output voltage is increased (Sakly et al, 2017). Thus, the diode D is at cutting state, the circuit is divided into two different parts. The output voltage remains constant as long as the time constant of the RC circuit is greater than the switching period.

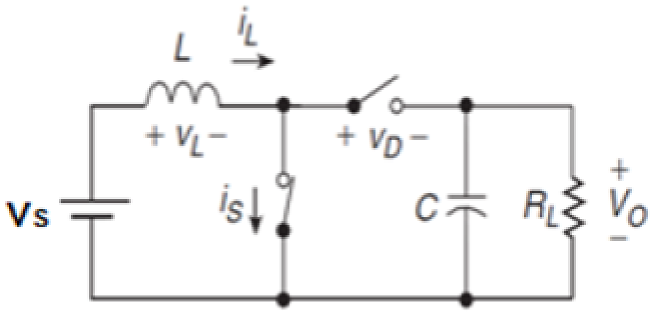

Figure 5.2: Transmission state of the semiconductor switch (Agrawal, 2001)

The circuit showing the cutting state of the semiconductor switch is shown in Figure 5.3. In this case the load is fed through the source.

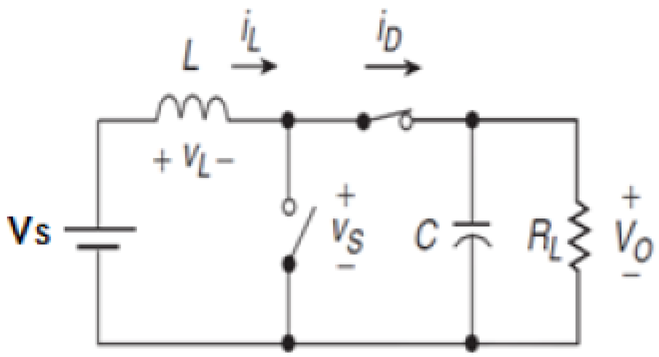

Figure 5.3: Cutting state of the semiconductor switch (Agrawal, 2001)

For analysis, first assumed that the circuit elements are ideal. Accordingly, the voltage drop across the key during transmission is zero, current or voltage conflicts don't occur during transmission and cutting. The voltage drop across the diode during transmission is zero. There is no lost on coil and capacitor. The operation of the circuit is periodic. That is, the current flowing through the coil is periodic and the values at the beginning and end of the switching period are the same. The transmission and cutting state of the semiconductor switch is made of constant frequency. And the value of the frequency provide to determine the period T. The transmission rate is expressed by D and the transmission time is equal to the DT value. The time that the switch is in the cutting state is expressed by (1-D) T. The coil current is continuous and is greater than zero. Since the capacity is considered large enough, the RC time constant becomes too large. For this reason, voltage fluctuations on the capacity in transmission and cutting conditions can be neglected. The voltage source Vs is fixed (Sakly et al, 2017).

5.2.1 Current passing through coil during the switch is at transmission state

The equivalent circuit during switch at transmission state is as shown in Figure 5.2. The voltage source supplies the coil and the rate of rise of the coil current varies according to the source Vs and the value L as follows.

$$V_L = V_S = L\, di_L/dt \tag{5.1}$$

If the voltage source is stable, the rate of rise of the coil current is positive and constant. Thus the coil does not go to saturation. This statement is shown below.

$$\Delta i_L / \Delta t = V_S / L \tag{5.2}$$

The semiconductor switch remains in transmission during the DT interval in a switching period. DT interval can be expressed as Δt. In the case of transmission of the switch, the net increase in the coil current is below.

$$\Delta i_L = (V_S / L) * (DT) \tag{5.3}$$

5.2.2 Current passing through the coil when the switch is at cutting state

The equivalent circuit when the switch is at cutting state, as shown in Figure 5.3. In this case, the voltage on the coil is expressed as follows.

$$V_L = V_S - V_O = L\, di_L / dt \tag{5.4}$$

In the case where the output voltage is higher than the source voltage (Vo>Vs), the voltage on the coil and the direction of the flowing current are negative with the following expression.

$$di_L / dt\ = V_S - V_O / L \tag{5.5}$$

When the switch is at cutting state, the interval is expressed by (1-D)T. Current through the coil as follows.

$$\Delta i_L = (V_O - V_S / L) * (1 - D)T \tag{5.6}$$

If the net change in a periodic current is zero,

$$V_O = V_S / 1 - d \tag{5.7}$$

If the inductor used in the circuit is not large enough, the current of the inductor drops to zero before the end of the period when the switch is in the cutoff, and the switch remains there until the switch is turned on again.

In this case, it is said that the circuit is operating in a disconnected current. If the current drops to zero at the end of the full period, then it is said that the engine is operating at the limit. Figure 5.4 shows the current and voltage characteristics of the circuit operating with cut-off current (Marei et al, 2003).

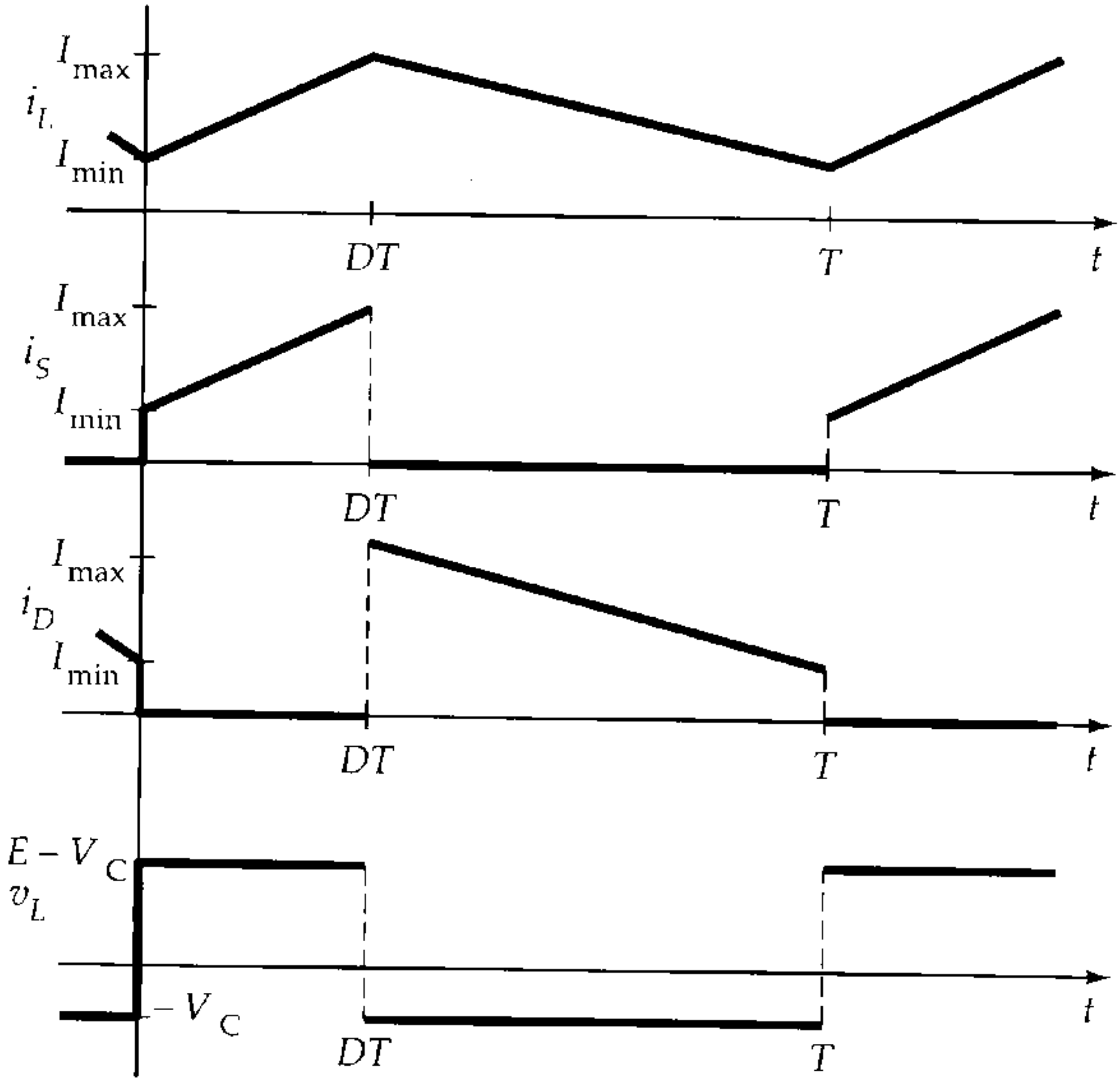

Figure 5.4: The current and voltage characteristics of the circuit operating at cut off state(Marei et al, 2003)

CHAPTER 6

FUEL CELL

6.1 General Information

FC is the system which produces electrical power from an electrochemical response of an appropriate combustion and oxidant. FC is a generator which transforms fuel chemical power straight inside electrical power by the electrochemical reaction of fuel and air.

In other words, hydrogen could merge with oxygen absent burning into the electrochemical response to produce electricity. The place where this reaction occurs can be named electrochemical FC either only the FC. Fuel cells are clean, quiet, free from moving parts and high efficiency, electricity and heat energy production technology from natural gas or other hydrogen containing gases.

Electricity is produced in the form of direct current (DC), after the FC reaction, that may also be explained as reverse reaction of electrolysis. Fuel cells are analogous to batteries and batteries in that they are generating electricity by an electrochemical process. The batteries and FCs transforms the stored power inside of electrical power by way of an electrochemical response. The provided energy can be limited to stored energy. On the other hand, fuel cells are the energy production systems that can continuously perform this conversion in the case of air and fuel are provided (Jia et al, 2005).

A FC and its operation are schematically shown in Figure 6.1.

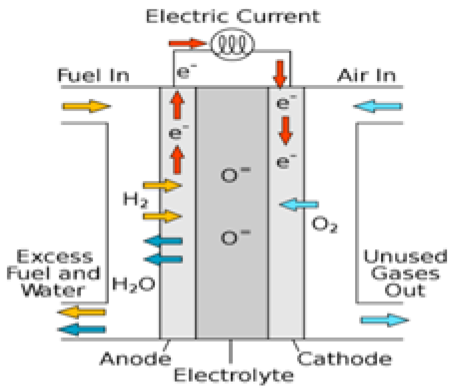

Figure 6.1: General structure and functioning of a fuel cell (Yi, 2003)

Basically, fuel cells comprise of electrolyte and any one of its surfaces keep in touch with anode and cathode electrodes which has the pervious-porous structure. That is, the electrodes are pervious and porous structure. And there is electrolyte between the electrodes. Gas fuel is sent to the anode (negative) pole or electrode of the fuel cell. Oxidizer (air or oxygen) is sent cathode (positive) pole or electrode of fuel cell. The potential difference between the anode and the cathode is a result of the electrochemical reaction of this fuel and air sent. This situation causes having an electron flow and electrical voltage. If heat, pure water and a carbon-containing fuel are used after reaction, the carbon dioxide is additionally released (Yi, 2003).

6.2 Working Principle of Fuel Cell

The chemical reaction in the fuel cell is the reverse of the electrolysis phenomenon. As is known, in the case of electrolysis, when two electrodes are left in pure water and a low voltage (12V) electric current is applied to these electrodes, the water dissociates into hydrogen and oxygen ions forming itself. The fuel cell consists of two electrodes. One of them is negative (anode) and the other one is positive (cathode). Electrodes are usually solid metals. Hydrogen is injected inside of the positive pole of FC, and Oxygen gets into its cathode part. Hydrogen atoms are separated into protons and electrons by the action of the catalyst.

$$H_2 \rightarrow 2H^+ + 2e^- \tag{6.1}$$

The separated electrons pass through an electric circuit and generate electric current. The protons move from the electrolyte to the cathode. The electrons which is completed the circuits are again connected to the proton of hydrogen and combine with oxygen to provide pure water vapor and heat to the water.

$$2H^{+} + 2e^{-} + 1/2O_2 \rightarrow H_2O + Heat \qquad (6.2)$$

Electrodes are usually made from a material that is a permeable carbon mixture. In order to the catalyst reaction is good, the catalyst parts must establish a good relationship between both proton and electron conductivity (Larminie and Dicks, 2002). Comparison between the efficiency of otto and diesel engine and PEMFC, the PEMFCs efficiency is approximately 2 times higher than the otto motor and 1.5 times higher than the diesel engine. It’s shown in Figure 6.2.

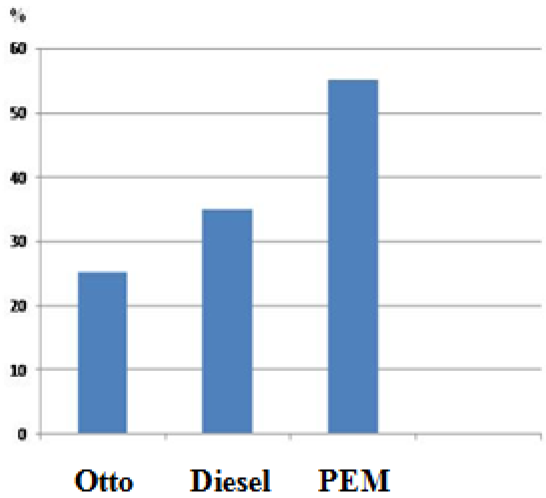

Figure 6.2: Comparison efficiency between otto, diesel and PEMFC (Yi, 2003)

Some of the main reasons for this are moving parts in internal combustion engines, and some of the resulting power is spent on friction of moving parts. Another reason for the low efficiency in internal combustion engines is that the hydrocarbons in the fuel do not burn completely. There are no moving parts on the fuel cylinders and there is no such thing as incomplete combustion (Yi, 2003).

6.3 Fuel Cell Losses

- Activation losses: The reaction that occurs at the surface of these lost electrodes is caused by the slowness of the reaction. Part of the generated stress during reaction is lost during electron transfer.
- Fuel jumping and internal current losses: losses due to waste fuel passing through the electrolyte and electrons passing through the electrolyte instead of the external circuit.
- Ohmic losses: Electrons and ions flow from the resistance of electrons and electrolytes. It is sometimes called resistive losses.
- Mass transfer or Concentration losses: This is caused by the variation of the concentration of the reactants on the surface of the electrodes. Concentration affects the tension, and thus such irreversibilities are called concentration losses. This is because the drop in concentration prevents sufficient transfer of the reactant to the electrode surface. Such losses are often referred to as mass transfer loss. Sometimes called Nernstian losses (Laughton, 2002).

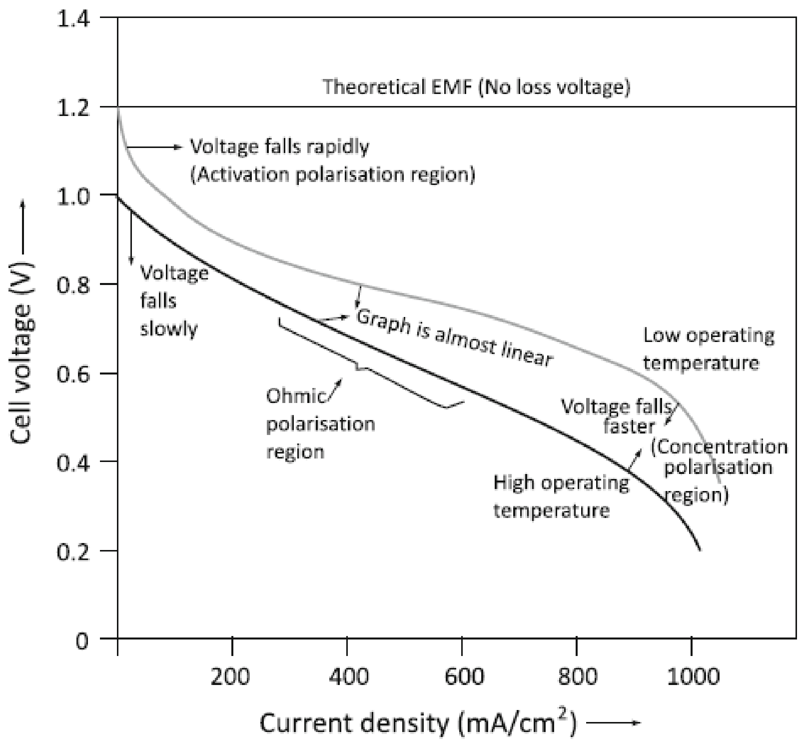

Figure 6.3: Polarization curve of fuel cell (Laughton, 2002)

6.4 Kind of FCs

Today, we may list the kinds of FCs that can be used like fuel. Kinds of FCs given on Table 6.1.

Table 6.1: Types of fuel cell and its properties (Swider et al, 2002)

Types of Fuel Cell	Mobile Ion	Operating Temperature	Electrical Efficiency
Proton Exchange Membrane Fuel Cell (PEMFC)	H^+	(30-100) °C	%40
Direct Methanol Fuel Cell(DMFC)	H^+	(20-90) °C	%20-30
Phosphoric Acid Fuel Cell (PAFC)	H^+	160-220°C	%55
Molten Carbonate Fuel Cell (MCFC)	$CO3^{2-}$	~650°C	%65
Solid Oxide Fuel Cell (SOFC)	O^{2-}	(500-1000) °C	%60-65
Alkaline Fuel Cell (AFC)	OH^-	(50-200) °C	%60-70

Table 6.2: More details about fuel cells (Swider et al, 2002)

Types of Fuel Cell	Electrolyte	Fuel /Oxidizer	Typical Stack Size
Proton Exchange Membrane Fuel Cell (PEMFC)	Proton Conducting Membrane	60% H2 /O2 ,air	1kW -250kW
Direct Methanol Fuel Cell(DMFC)	Proton Conducting Membrane	CH3 OH/O2 , air	1kW
Phosphoric Acid Fuel Cell (PAFC)	Liquid Phosphoric Acid	Natural Gas, Biogas H2 /O2 ,air	400 kW 100 kW Module
Molten Carbonate Fuel Cell (MCFC)	Alkaline Carbonate	Natural Gas, Biogas, coal gas H2 /O2 ,air	300 kW -3MW 300 kW Module
Solid Oxide Fuel Cell (SOFC)	Ceramic	Natural Gas, Coal gas, Biogas, H2 /O2 ,air	1 kW -2MW
Alkaline Fuel Cell (AFC)	Caustic Potash Solution	H2 / O2	10-100kW

Table 6.3: Comparison of fuel cells (D'Arco et al, 2005)

Types of Fuel Cell	Application	Advantages	Challenges
Proton Exchange Membrane Fuel Cell (PEMFC)	Back Up, Portable Power, Distributed Generation, Specialty Vehicles	Quick Start up time, Low Temperature, Solid electrolyte reduces corrosion and management problems	Expensive catalysts, Sensitive to fuel impurities
Direct Methanol Fuel Cell(DMFC)	Vehicles and small appliances	Use an energy dense liquid without the need to highly compress a gas.	Lifetime limited Require even more platinum than hydrogen fuel cell
Phosphoric Acid Fuel Cell (PAFC)	Distributed Generation	Higher Temperature enables CHP, Increase tolerance of fuel impurities	Pt catalyst, Long Start up Time, Sensivity
Molten Carbonate Fuel Cell (MCFC)	Electric Utility, Distributed Generation	High Efficiency, Fuel flexibility, Suitable for CHP ,Can use a variety of Catalysts	Long Start up Time Low Power Density High temperature corrosion
Solid Oxide Fuel Cell (SOFC)	Electric Utility, Distributed Generation, Auxiliary Power	High Efficiency, Fuel flexibility, Suitable for CHP and CHHP, Hybrid/GT Cycle, Solid Electrolyte	High temperature corrosion, Long Start up Time
Alkaline Fuel Cell (AFC)	Military, Space	Low Cost Component Cathode reaction faster, it leads to higher performance	Management or electrolyte, sensitive to CO2 fuel and air

6.5 Preferences of Fuel Cell

As is known, the world population is constantly in an increase, and there are some needs that this increase can bring. Naturally, energy and energy sources are at the forefront of these needs. For example; there are over one billion internal combustion engines in the world. Therefore, different energy sources are needed to make these engines work. In addition to the thought that the amount of petroleum-derived energy resources will be reduced or consumed in the coming years, it is the fact that the distribution of petroleum product fuels elsewhere, especially to distant countries, is troublesome and costly, directing scientists and businessmen to other energy source.

Due to the rapid climate change, the Kyoto protocol in Japan in 1997 proposed reducing greenhouse gas emissions and replacing other renewable energy sources. As is known, some of the rays of the sun that come into the world are reflected back. These reflected rays are trapped by the most harmful greenhouse gases, carbon dioxide and other greenhouse gases. When the sun's rays reflected back from the Earth are trapped by carbon-containing gases, the heat accumulates in the gas layer that surrounds the earth. This causes the temperature to increase on the earth (Larminie and Dicks, 2003).

6.6 Advantages of Fuel Cells

The most important technology to meet these two important factors mentioned above is the fuel cells. The advantages of FCs are;

- The hydrogen's usage as fuel, thanks to hydrogen's abundace in nature
- Pure water vapor and heat extraction as waste
- No moving parts (piston, miller, etc.)
- Quiet work,
- Greater efficiency than petrol and diesel engines.

The advantages of fuel cells over other energy systems are listed below:

- Fuel oil works with higher efficiency than thermal energy systems. While the efficiency of the system in generating electricity from thermal systems is affected by the "Carnot Cycle Criteria", there is no such interaction in fuel system.

- In thermal systems, the efficiency of electricity generation can not exceed 35-40%, while the efficiency of fuel systems is about 70%.
- The amount of emissions from fuel cells in the fuel cell is negligible compared to other fuels. As a by-product, a single water is formed. When there are no CO, NOx, unburned hydrocarbons, and other pollutants in the fuel cylinders, there is a negligible amount of nitrogen oxides when the air is used as oxidizer, and a very low amount of CO2 when hydrocarbons are used. Nowadays, when many legal restrictions are applied for environmental pollution and human health, while other technologies are increasing the cost too much, environmental friendly of this system leads to a very valuable alternative fuel.
- The system does not cause any noise pollution in the fuel tank where there is no moving part.
- Because of the large number of fuel that can be used in fuel cells, it can be used in many different areas due to the ease of use of fossil and alternative fuels.
- Fuel cells can be produced in the desired size and capacity. They have a simple structure. They have a power range from 10 W to 4.5 kW according to their size. Their size can be as small as a hand-held bag or as big as a fridge.
- They are modular. They can be used and placed wherever they are needed.
- Waste heat generated as a by-product in fuel system can be recovered.
- Fuel cells are durable and safe systems.

6.7 Disadvantages of Fuel Cells

- Fuel cell use is a system that requires a lot of knowledge and advanced technology.
- It is a more expensive system than other systems.
- It takes a long time and a lot of money for its applications to be realized with full efficiency.

As can be understood from the items listed above, increasing the application areas of fuel pills will benefit in many ways. There are the following disadvantages when applying;

- The lack of hydrogen production facilities and some problems in storage.

- The fact that the fuel cell vehicles to be produced are costly due to the fact that the more rapid production has not been passed.
- The lack of enough generators for today.
- Some fuels are expensive to produce and distribute (O'Hayre et al, 2006).

6.8 Comparison between FC and Battery

- **Either of them generate electricity:**When the battery provides electric by power, this can store into battery. However FC provides electricity by combustible in an exterior. That means, when the battery might work lifeless, a fuel cell can do electricity according as fuel is provided. About hydrogen FCs, hydrogen is combustible so it stocked in a deposit linked to FC. While hydrogen in deposit, you can recharge it, translocate it with whole deposite.
- **Refueling and Refilling:** When there are varied types of hydrogen tanks and methods for stocking hydrogen, more accurate one is that charging hydrogen deposits is quicker than refilling batteries.
- **Lifetime:** Nowadays FCs life time is a few year more than battery that provides low and low power return always you can refill. Translocating electricity resource low frequently protect your money extra work and decreases ambience effect of recycling.
- **Intrinsic Differences:** Hydrogen FC has the on system. Platinum catalyst keeps in touch with negative pole and positive pole that are gases. Reactants can be exteriorly provided without refilling necessary. However battery has off system. Positive pole and negative pole parts can be metal. The needed cyclical refilling consumes reactants inwardly.
- **Other Properties Comparison:** According to research that FC is superior from advanced battery on six major counts. These are having low massiveness, coats low gaps on the vehicle, produce low planthouse gases, cost less, requires less well to wheels energy and takes less time to refuel (Thomas, 2009).

CHAPTER 7

PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL

7.1 Structure and Working Principle of PEMFC Fuel

The most elegant fuel with regards to design and operation cell is PEMFC. First PEMFC was developed by General Electric in 1960 for NASA. Here, a solid polymer electrolyte membrane is placed between two platinum catalyzed porous electrolytes. Polymer electrolyte membranes are also referred to as fuel cell. It has more power density, lower volume and lower weight than other fuel cells. A thin polymer membrane is used as the electrolyte in the fuel cell. The membrane, which has a micron-level thickness, is a proton-permeable structure. Operating temperatures are below 100 °C and generally in the range of 60-80 ° C (Haraldsson and Wipke, 2004).

The use of noble metals as catalysts (usually platinum) causes to increase the cost. The platinum catalysts are hypersensitive to carbon monoxide, which requires the decomposition of carbon dioxide which may be present in the fuel. This leads to additional processes and costs. Against this probing, in some designs, platinum/ruthenium catalysts with very low carbon monoxide sensitivities are used. Figure 7.1 shows the reactions occurring in the PEM fuel cell. Also the reaction equations are given below (Cheddie and Munroe, 2005).

Positive pole response: 2H2 ~ 4H + + 4e- (7.1)

Negative pole response: 4H + + 4e- + ½O2 ² 2H2O (7.2)

Sum response: 2H2 + O2 ® 2H2O + Electric energy (7.3)

From the point of view of the work, membrane should transmit hydrogen ions (protons) because if the electrons are transmitted, there is a short circuit in the FC. Membrane should not allows any gas to cross to the opposite side of the cells. In addition to this, membrane should be enduring with a reduction ambience in negative pole side. Also, it should be enduring to the harsh oxidizing ambience in positive pole side.

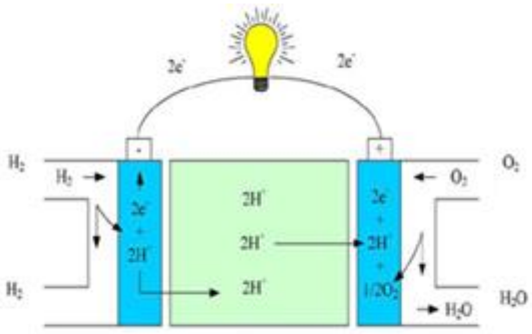

Figure 7.1: General working principles of proton exchange membrane fuel cell (Haraldsson and Wipke, 2004)

The protons formed by the separation of the electrons from the hydrogen sent to the anode, and the electrons reach the cathode from a other circuit. The air / oxygen which is sent to the cathode is reacted with the incoming protons and electrons. With this situation, the circuit is completed and the water is released. This fuel cell, which is composed of the solid membrane, has ion permeability of the membrane. Therefore the performance is significantly related to the membrane's humidity. For this reason, the membrane must be kept at a certain moisture level. For this purpose, usually hydrogen and air are sent to the system through a humidity unit. The system usually includes a water management unit to control and maintain this level of humidity. Otherwise, if this moisture level is not provided, the membrane may be damaged, as there will be significant reductions in performance. For this reason, many studies have been carried out on the performance of the fuel cell humidifier on performance. This type of fuel cell is especially preferred for vehicle applications and some stationary applications. Fast response time, high power density and compact construction are the main reasons for using vehicle application. Their efficiency level is around 50% (Spiegel, 2008).

The proton exchange membrane fuel cell consists of three basic structures. This structures have an important role in their operation. A detailed view of the components of a PEMFC and operating system given in Figure 7.2. These three basic structures are explained in detail below.

7.1.1 Electrolyte (Membrane)

The basic function of the membrane is to realize the ionic interaction between the anode and the cathode. It separates the two gases (hydrogen and air) entering into the reaction at the same time. The most important characteristic of the membrane used in the PEM fuel cell is the decrease of proton or hydrogen ion transmission with drying. The excess amount of water causes water overflow in the electrodes and back pressure formation. These cause a significant impact on fuel cell performance. Therefore, good water management is required on the membrane. The heat from the electrochemical reaction resulting from the fuel cell is important to remove it from the system. That is, the necessity of keeping the fuel cell temperature constant in needed for a suitable cooling system, especially in medium and large-scale applications.

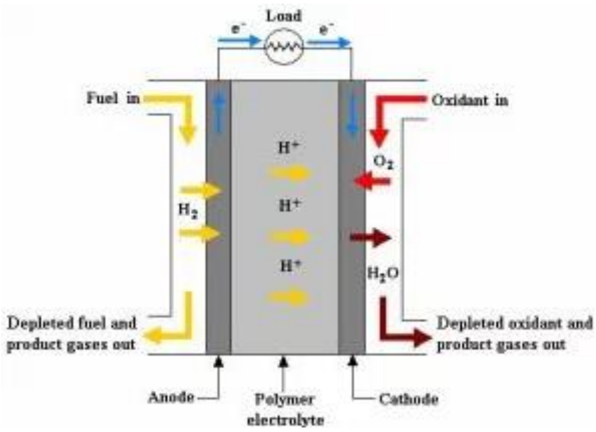

Figure 7.2: Detailed display and operating principles of PEM fuel cells components

Perfluorocarbon based ion exchange membranes are used in PEM fuel cell. Today's mostly used the standard electrolyte is Nafion. It was developed by the Dupont company in the 1960s. And it is a teflon based material. Various series have been produced. Today the use of Nafion 115 and Nafion 117 are common. Nafion membranes have thermal and chemical stability. The most widely used membrane, Nafion, is based on the principle of liquid water humidification of membranes for the transfer of protons. Because of drying the membrane in the absence of water, operating the system should not be suitable more than 80-90 °C (Sammes, 2006).

Other kinds of membranes are depending on polybenzimidazole (PBI) and it can arrive to 210 °C exteriorly the need for any water gubernation.

Among the major advantages of these membranes are better efficiency at high temperature, power density, easier cooling (due to large warmth variation), lower susceptibility to CO empoisoned and favourably control (due to the absence of membrane water management process). However, these last kinds of membranes are not very mutual. Nafion are still using at research laboratories. Today, membrane performance and stability are satisfactory levels. Significant disadvantage is the high costs.

7.1.2 Electrodes

The electrodes are gas diffusion members and play a role in separating hydrogen into protons and electrons. Electrodes are pressed to a thickness of 5-50 μm. Usually the catalyst which is prepared by platinum material are the most used catalysts in both electrodes. Because of the expensiveness of platinum, efforts to reduce platinum usage intensity are increased. The catalyst which is used in the PEM fuel cell is adversely affected by CO, CO2 and hydrocarbons. This leads to increasing the necessity of the purity of the gases that sent to the fuel cell. It reveals purification cost (Barbir, 2006).

7.1.3 Bipolar plate

Carbon graphite plates are used the purpose of current collection, distribution and thermal management for many PEM application. Its thickness is approximate 350 μm. Often, the cooling surfaces which are integrated with the bipolar plate are required for fuel cell cooling. Air or water used as a refrigerant is passed through these surfaces and cooling is executed. For the fuel cell efficiency, the contact resistance of the bipolar plates must be minimum. And it is desirable that the conductivity is maximum. PEM fuel cells, due to its compact construction, can be used for vehicles and other mobile phones. However, water gubernation is vital to productivity. Because so much water wets the membrane, less water causes drying. Either situation the energy output drops. Water gubernation in PEM systems is very difficult. There are various solutions such as the integration of electroosmotic pumps for water management.

In addition, the platinum catalytic on the membrane is handily empoisoned by carbon monoxZide and the membrane is fragile to substances such as metal ions from the abrasion of metallic bipolar plates.

In some PEM systems which are using methanol, methanol is reacted to form hydrogen is a highly complicated process and involves the reaction products in CO gas it needs to be purified. It is necessary to use a platinum-ruthenium catalytic as some carbon monoxide inevitably reaches the membrane. Carbon monoxide stage should not pass 9 ppm. Moreover, the starting time for such a processing reactor is approximately 30 minutes. Interchangeably, methanol and different biofuels can be nourished directly to the PEMFC exteriorly being processed to make methanol fuel cells (DMFC) directly. The operation of such devices is rather limited. The efficiency of PEM varies between 40-50% (Husseini, 2012).

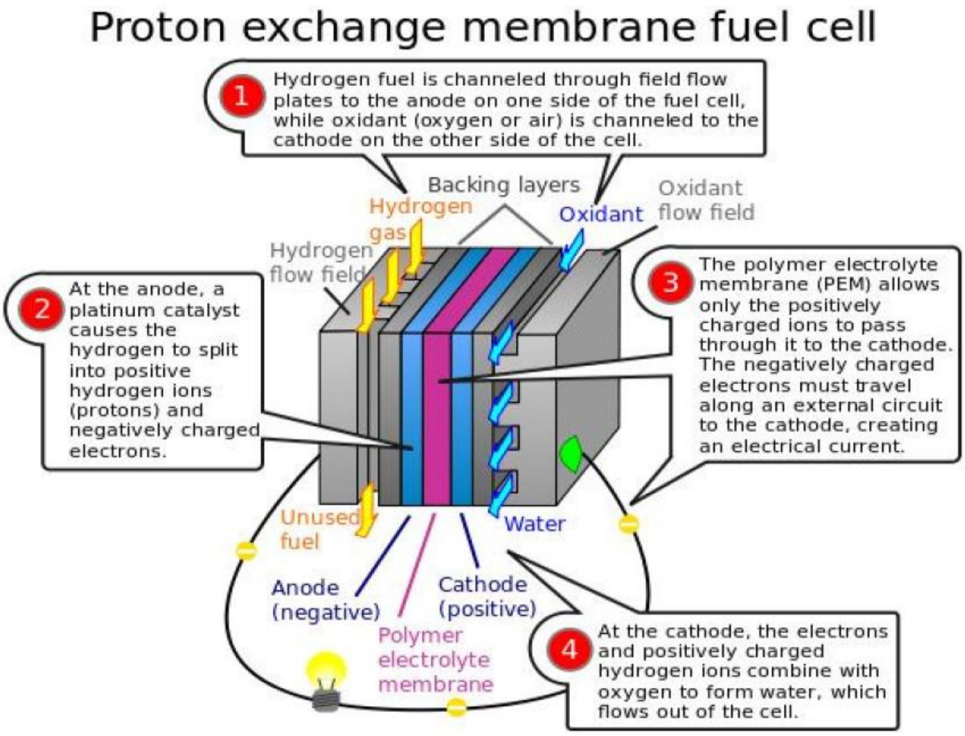

Figure 7.3: Step by step working principle of PEM fuel cell (Haraldsson and Wipke, 2004)

CHAPTER 8

SYSTEM DESCRIPTION

8.1 Introduction

In the scope of the thesis, instead of the battery for the unmanned underwater vehicle, the PEMFC was integrated. Normally, power required to operate unmanned underwater vehicle is 4.5 kW which was obtained with 3 batteries. In this case, a 4.5 kW FC will be integrated instead of a 4.5 kW battery. The output tension of boost converter must be 90 V for vehicle to be able to operate. The output voltage is 30 V while the FC produces 4.5 kW of energy. To obtain the required 90 V voltage and to raise the output of the FC, an amplifier DC-DC converter which is called boost converter must be designed to produce a constant voltage under all conditions. In this section, the hydrogen consumption by the fuel cell, fuel cell, the DC-DC converter circuit to the design and obtained results are presented.

8.2 Design FC and Boost Converter

This section describes the design of the upgrading converter. Previously, it explained how the converter works. Only design steps will be shown in this section. The converter will convert the output voltage of the model of Power cell’s 4.5 kW S2-50c fuel cell to the level used by the unmanned underwater vehicle which is 90 V. The current-voltage structure of the FC is shown in Figure 8.1.

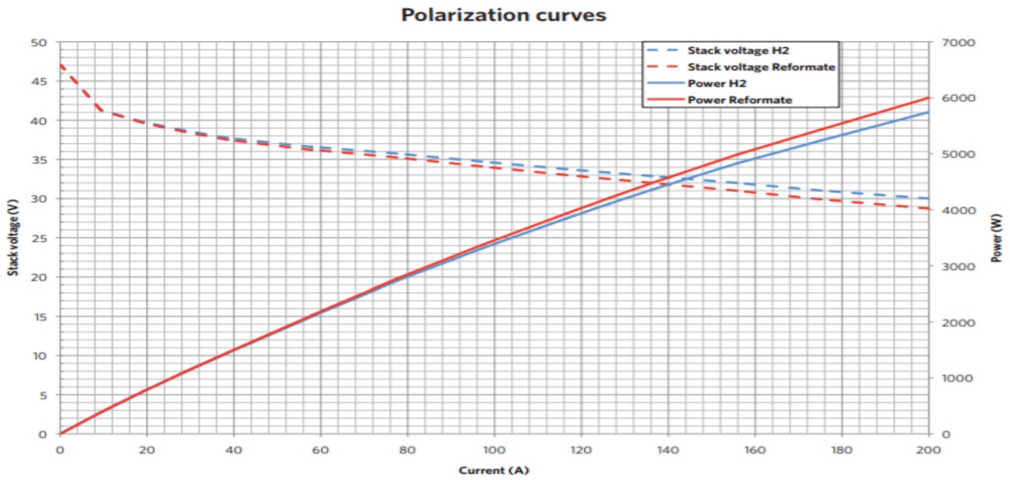

Figure 8.1: Polarization Curve of Powercell S2-50c 4.5kW PEM Model FC

FC output voltage is 30 V and current is about 150 A. When the fuel cell is working, the converter output voltage is planned 90 V and current is 50 A. Therefore, the converter to be used should be the boost type.

Table 8.1 The required design parameters of boost converter

Parameter	Explanation	Value
Pmax	Maximum Output Power	4500w
Fsw	Switching Frequency	20kHz
Vs	Nominal Input Voltage	30 V
Vsmax	Maximum Input Voltage	46 V
Vo	Nominal Output Voltage	90 V
Δ_{Is}	Current ripple	%40
Δ_{V}	Voltage ripple	%10

8.2.1 Inductor selection for boost converter

The calculation of duty cycle,

$$D_{min} = 1 - V_{imax}/V_o$$

$$D_{min} = 1 - 46/90$$

$$D_{min} = 0.49$$

$$D_{max} = 1 - V_{imin}/V_o$$

$$D_{max} = 1 - 30/90$$

$$D_{max} = 0.66$$

$$0.49<D<0.66$$

In planning system design, Duty cycle is selected 0.5.

Steady state inductor current calculation,

$$I_{min} = V_{imax}/R * (1 - D_{min})^2$$

$$I_{min} = 46/1.8 * (1 - 0.49)^2$$

$$I_{min} = 98.25 \text{ A}$$

$$I_{max} = V_{imin}/R * (1 - D_{max})^2$$

$$I_{max} = 30/1.8 * (1 - 0.66)^2$$

$$I_{max} = 144.2 \text{ A}$$

The current ripple will determine the inductance,

$$\Delta_{Imax} = \%40 * I_{max}$$

$$\Delta_{Imax} = \%40 * 144.2$$

$$\Delta_{Imax} = 57.7 \text{ A}$$

$$L_{min} = V_{imax} * D_{min}/\Delta_{Imax} * f_{sw}$$

$$L_{min} = 46 * 0.49/57.7 * 20x10^3$$

$$L_{min} = 19.5\ \mu H$$

$$\Delta_{Imin} = \%40 * I_{min}$$

$$\Delta_{Imin} = \%40 * 98.25$$

$$\Delta_{Imin} = 39.3\ A$$

$$L_{max} = V_{imax} * D_{max}/\Delta_{Imin} * f_{sw}$$

$$L_{max} = 30 * 0.66/39.3 * 20x10^3$$

$$L_{max} = 25.2\ \mu H$$

In the circuit, an inductor is used to guarantee the continuity of the current.

8.2.2 Capacitor selection

The voltage ripple will determine the capacitance

$$\Delta_{Vout} = \%10 * V_o$$

$$\Delta_{Vout} = \%10 * 90$$

$$\Delta_{Vout} = 9\ V$$

$$C_{min} = V_o - V_{imax}/\Delta_{Vo} * R * f_{sw}$$

$$C_{min} = 90 - 46/9 * 1.8 * 20x10^3$$

$$C_{min} = 135.8\ \mu F$$

$$C_{max} = V_o - V_{imin}/\Delta_{Vo} * R * f_{sw}$$

$$C_{max} = 90 - 30/9 * 1.8 * 20x10^3$$

$$C_{max} = 185.2\ \mu F$$

8.2.3 Selection of semiconductor switch and diode elements

The semiconductor devices has to be selected from the given semiconductor companies, i.e., IXYS or Semikron. To begin with selecting a transistor, it is a fact that the operation voltage, current and operation frequency is really significant points. The system's maximum voltage is 46 V. To select a suitable range, 50% more should be added to the maximum value. In fact, the selection values can be found by adding 50% more to the all critical selection parameters of the system. The selection values can be illustrated as;

$$\mathrm{Vsw_{max}} = 1.5\mathrm{xV_{imax}} = 1.5\mathrm{x}46 = 70\ \mathrm{V}$$

$$\mathrm{Iswrms_{max}} = \sqrt{\mathrm{d}}1.5\mathrm{xI_o} = \sqrt{0.60}\mathrm{x}1.5\mathrm{x}50 = 58\ \mathrm{A(rms)}$$

$$\mathrm{Iswpeak_{max}} = 1.5\mathrm{xI_o} = 1.5\mathrm{x}50 = 75\ \mathrm{A}$$

According to the results, the switching voltage is higher than 70 V, and rms current is higher than 58 A. Whereas, the peak current operates at least 75 A. In order to select the switch, the parameters are important role. The data for this element are given in Table 8.1.

Table 8.1: Switch and Diode parameters which company supported

IGBT SWITCH		DIODE	
PARAMETER	MIXD80PM650TMI	PARAMETER	MDD26-08N1B
V_{ds}	100 V	V_{RRM}	100 V
$I_{d(25)}$	75 A	I_F	60 A
$V_{ce(SAT)}$	1.5 V	V_F	0.8 V
t_f	40 ns	C_J	27 pF
t_r	45 ns		
t_{on}	25 ns		

8.3 Controller of Duty Cycle for Boost Converter

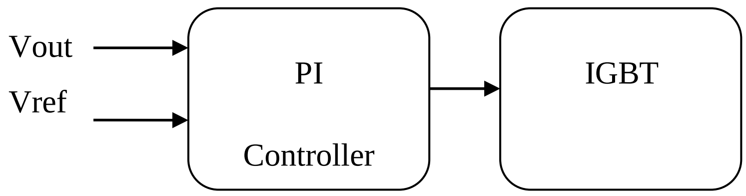

Figure 8.2: PI controller of duty cycle for boost converter

FC output voltage and current vary according to load at the output of the boost converter. Therefore, a boost converter was designed to get the voltage needed to operate our unmanned underwater. The duty cycle controlled by the PI-based feedback loop is designed so that this boost converter can deliver a constant voltage. First, the desired constant voltage Vref is selected.

The specified Vref and Vout PI are connected to the control of the controls. There are 2 parameters of PI controls. These are Ki and Kp. Kp was chosen as 0.0005 and Ki was chosen as 0.15 in order to give the desired output voltage. A function has been added to calculate the duty cycle at the output of PI controls. The duty cycle calculated from this function goes to the IGBT.

In addition, when the output voltage of the boost converter changes with this function of D is recalculated and goes to the IGBT and the selected Vref value is obtained.

8.4 Information about Selected Fuel Cell

For the unmanned underwater vehicle, the PowerCell S2-50C fuel cell which has the power of 4.5 kW is selected. FC nominal voltage is 30 V and rated current is 150 A. The unloaded voltage is about 46 V. The technical characteristics of the selected fuel battery are given in Table 8.3.

Table 8.3: Powercell S2-50C Fuel Cell Specifications

Physical Data	S2-50C
Length(mm)	148
Height(mm)	199
Width(mm)	480
Nominal Power Output (kW)	4.5
Voltage Output(V)	25-50
Nominal Voltage(V)	30
Nominal Current(A)	150
Maximum Current Output(A)	200

8.4.1 The main advantages of powercell s2-50c fuel cell

- PEMFC technics, quick work and close down
- Fuel flexible, for use with pure hydrogen or reformate gas
- Less compress reduce
- Fluid cooling, wide operating conditions
- Compelling model; for using in vehicle implementation

8.5 Required Hydrogen for Fuel Cell

Gaseous hydrogen was selected for the selected 4.5 kW fuel cell.

8.5.1 Gaseous hydrogen

Condensed Hydrogen provides the easiest and cheapest way for storing fuel and besides it takes benefit of unnecessity prior processing. As hydrogen in the gases that have less power intensity, very high compress (up to 690 bar) are generally implement to maximize the hydrogen ingredient when behaves the use of more weighty storage tanks to prevent mechanical defect overdue to more compress.

Hydrogen bottle can be made of more hardness steel or compound fiber. The compressed hydrogen varies around especial energy of 1.5-2.3 kWh/kg and power intensities are around 0.4-0.9 kWh/L.

According to given information, the hydrogen required for 4.5 kW fuel cell system is calculated as follows.

1 kg hydrogen specific energy is 1.6kwh/kg.

1 kg hydrogen	1,6kwh/kg
X	4,5Kwh/kg

$$X = 4.5\text{Kwh}/1.6\text{Kwh/kg} = 2.81 \text{ kg}$$

$$X = 2.81 \text{ kg}$$

2.81 kg of hydrogen is required to generate 4.5 kWh of energy for Fuel Cell

1 Lt Hydrogen energy densities 0.5 kWh/L

1 L hydrogen	0,5 kwh/L
X	4,5Kwh/kg

$$X = 4.5\text{Kwh}/0.5\text{Kwh/L} = 9 \text{ L}$$

$$X = 9 \text{ L}$$

The weight of the battery 43 kg. Fuel cell 14 kg + hydrogen tank (0.64 kg) + 2.25 kg (hydrogen)

Total weight = 17.65 kg

Table 8.4: Comparison battery and fuel cell for AUVs energy system

	3*1,5kw battery	**4,5kw fuel cell stack + hydrogen tank + hydrogen**
Voltage	30 v	30 V
Current	48 A	150A
Dimension(L x W x H)	3*(38,4*13,3*21)	(14,8*48*19,9)
Weight	3*14,3=42,9 kg	13,9kg + 0,64 + 2,25 = 17,65 kg

8.6 Simulation Modeling and Results

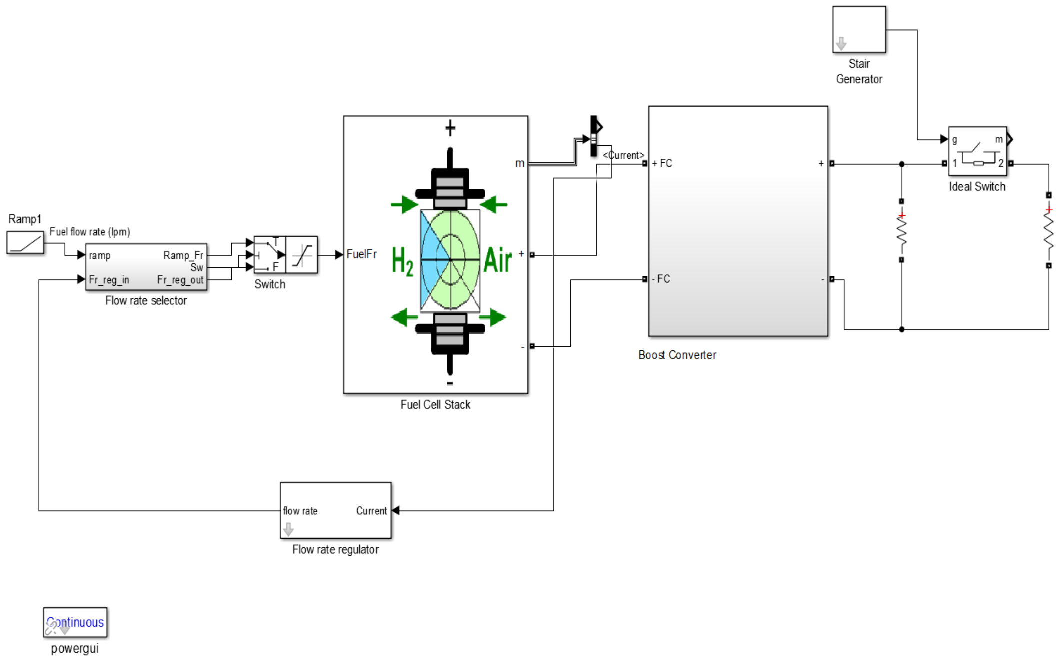

Figure 8.3: Structure of the system which designed in Matlab Simulink

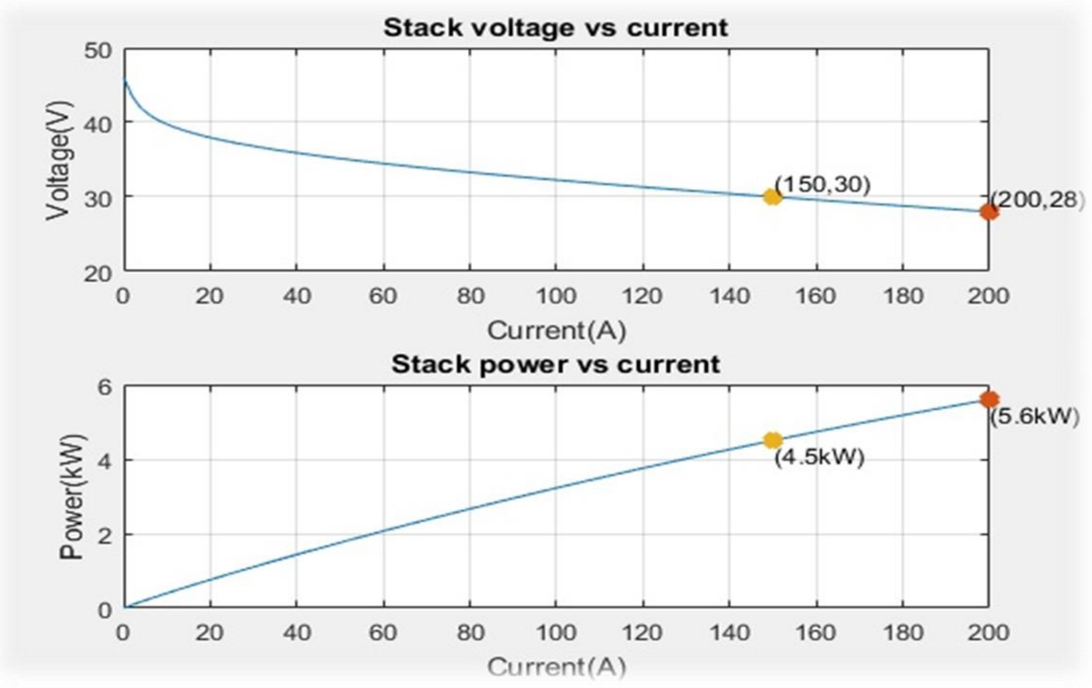

Figure 8.4: Polarization curve of designed 4.5kW PEM Model Fuel Cell on Matlab

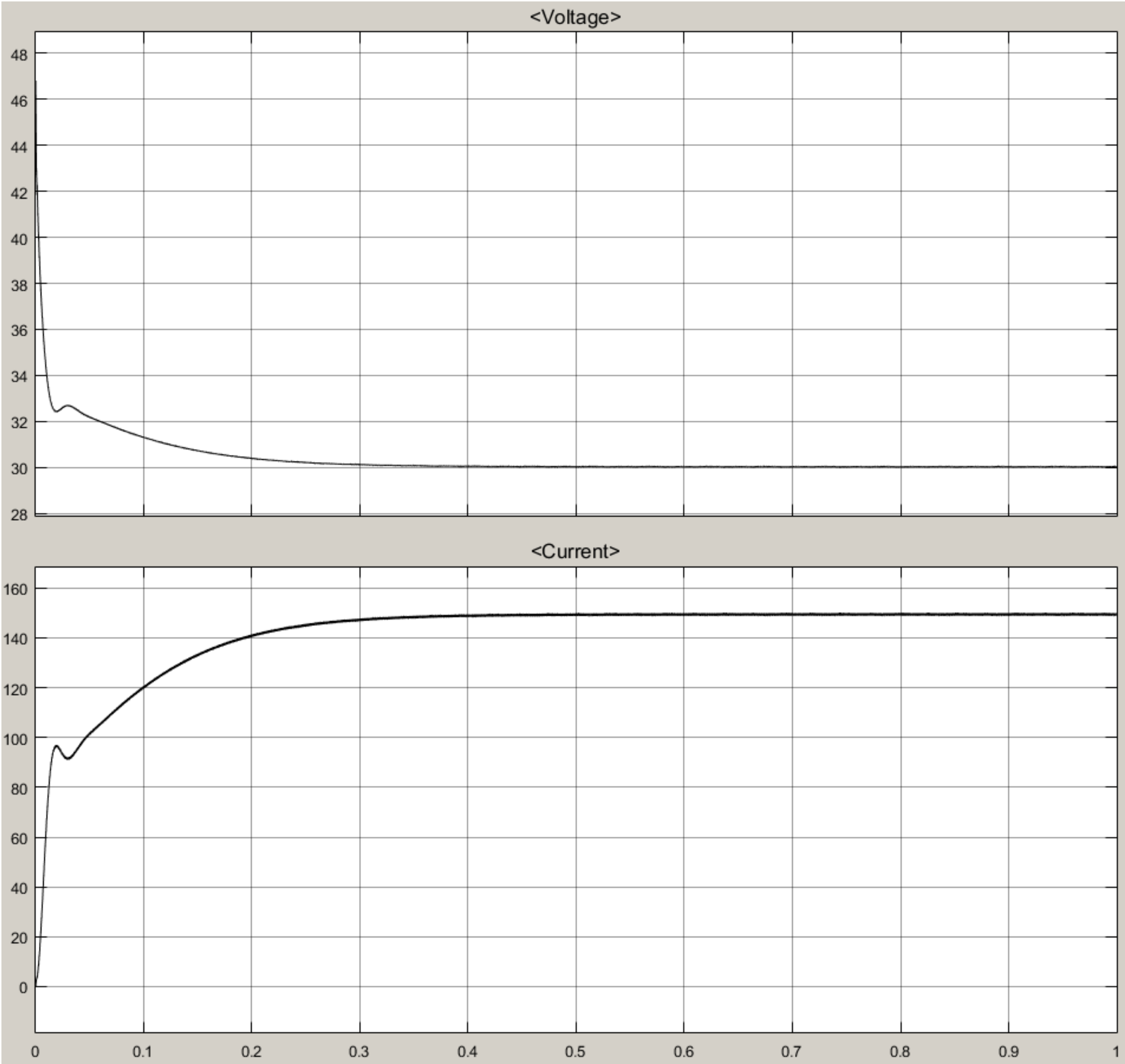

Figure 8.5: Output current and voltage of fuel cell

According to Figure 8.5, the fuel system’s output voltage is reached to 30 V and output current is 150 A.

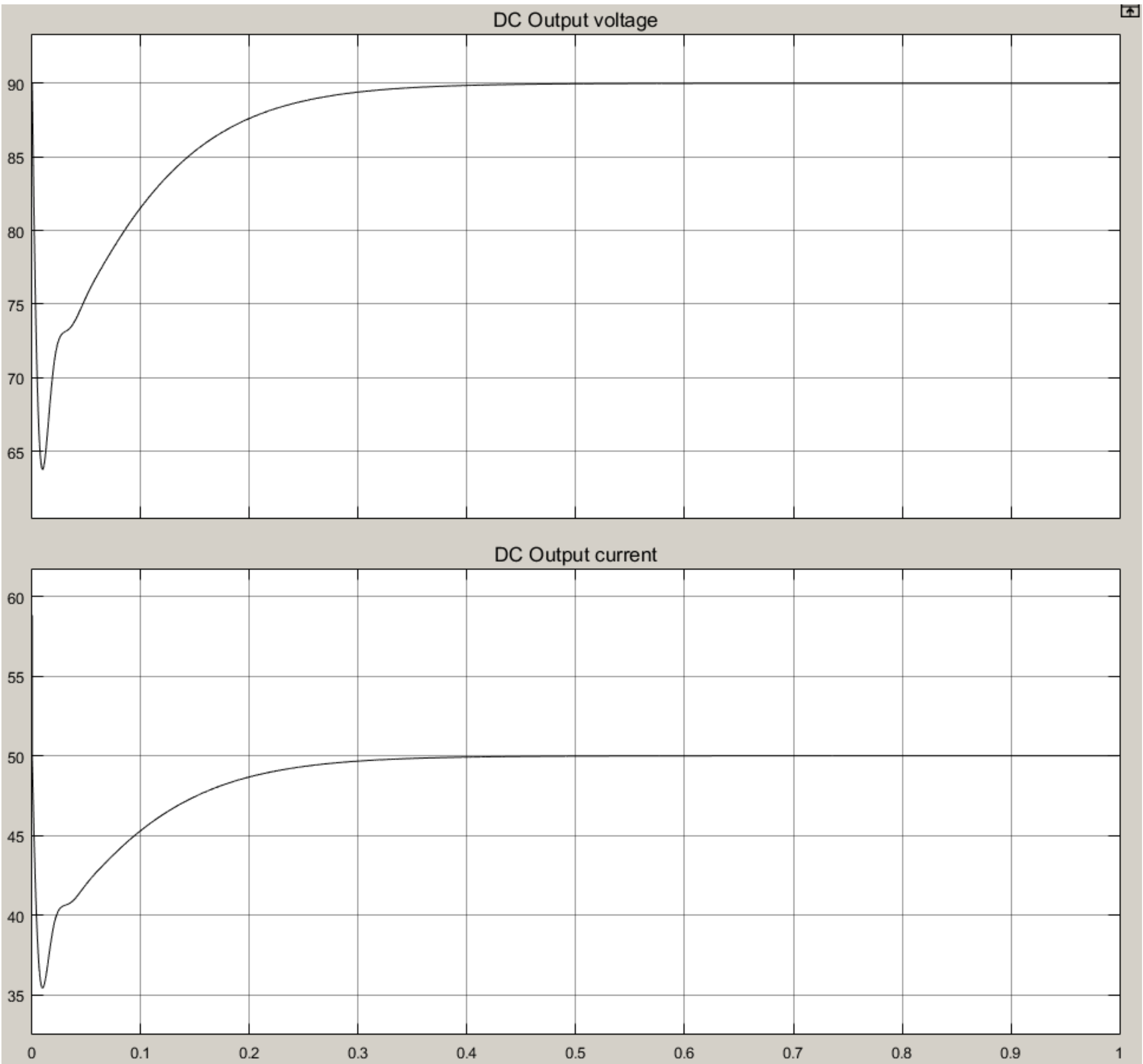

Figure 8.6: Output voltage and input current of converter

Figure 8.6 depicts that the result waveforms of boost converters. By using boost converter voltage is increased to 90 V and current is around 50 A.

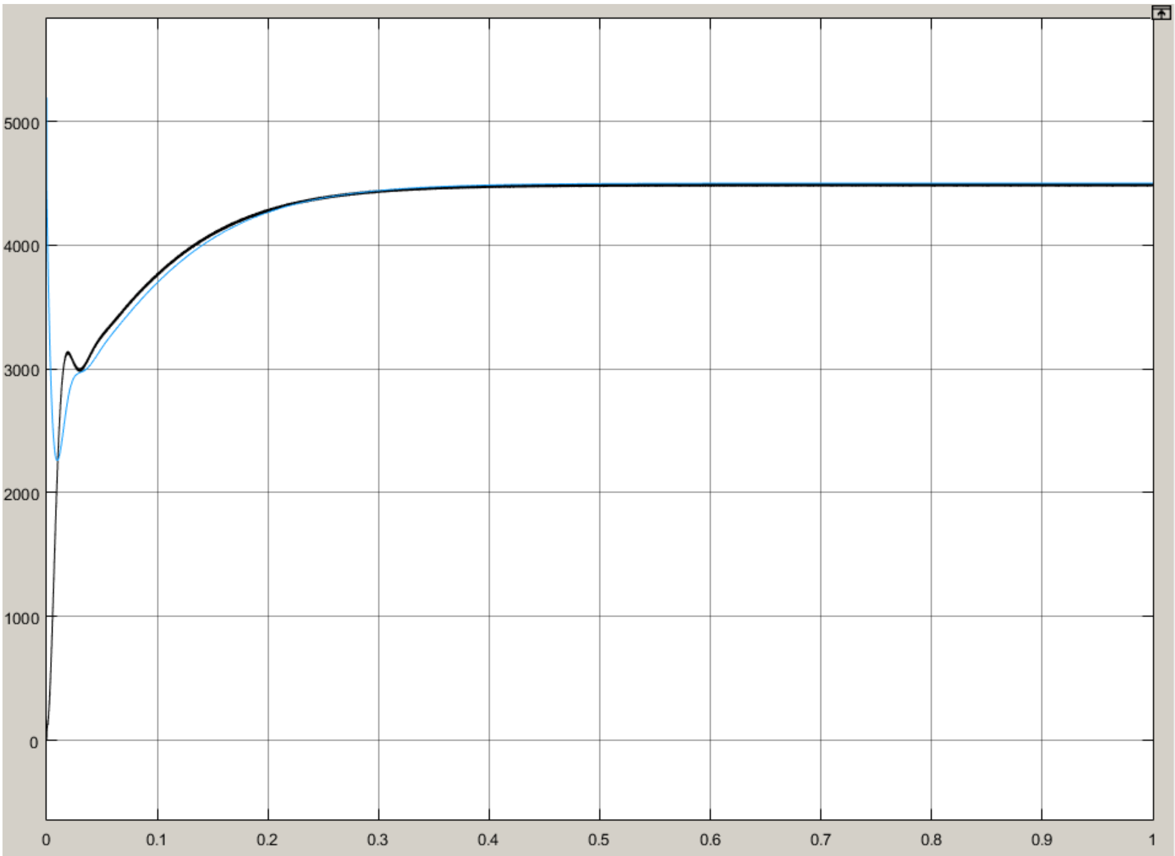

Figure 8.7: Output power and input power of converter

Figure 8.7 shows the output power and input power. These are need for efficiency calculation.

Input power (Pi) = 4528 W

Output power (Po) = 4500 W

$$ \eta = P_o/P_i \tag{8.1} $$

$$ \eta = 4500/4528 $$

$$ \eta = \%99 $$

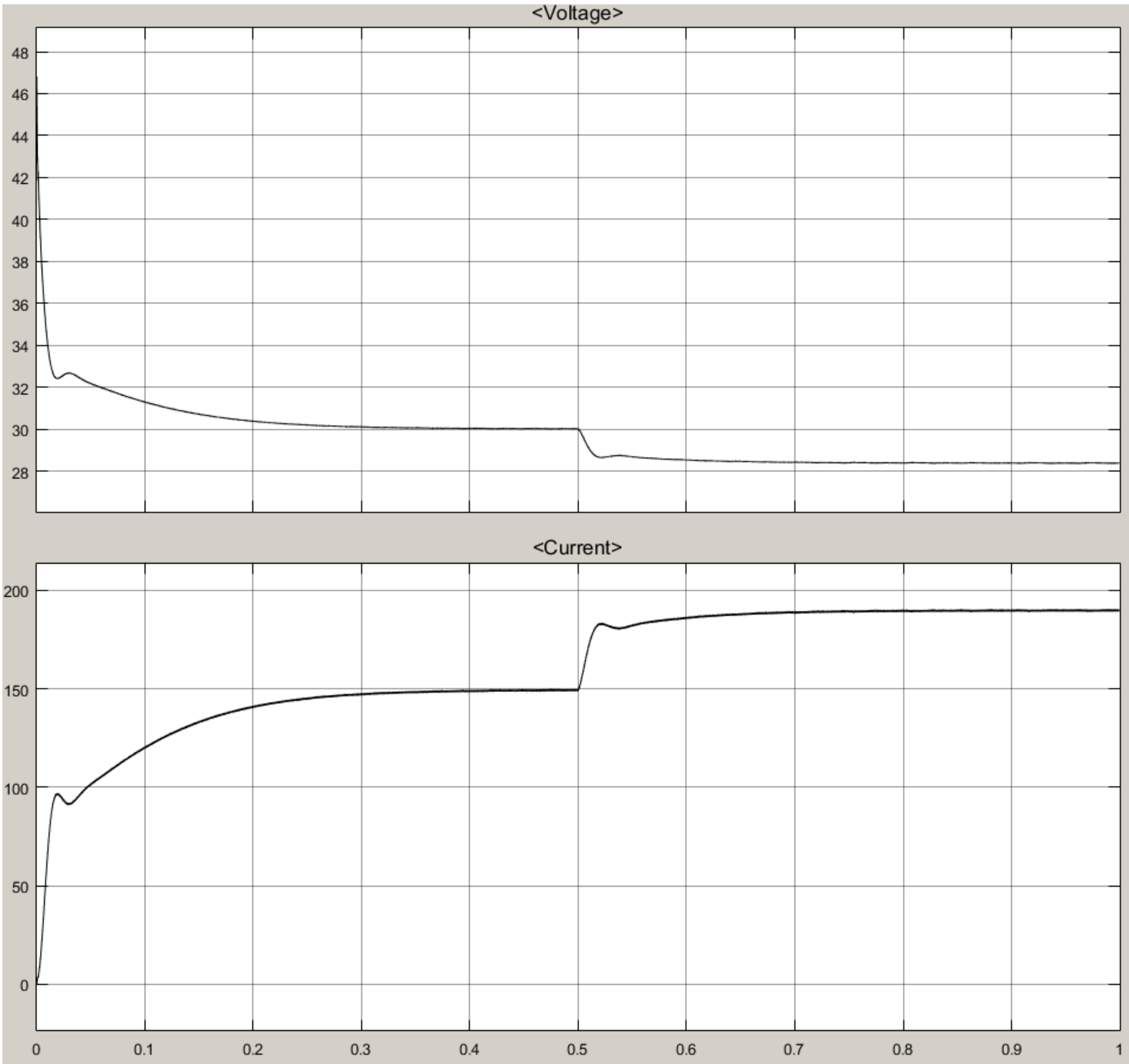

Figure 8.8: Output current and voltage of fuel cell at t=5 increase load

According to graph, AUV's required power from t=0 to t=5 duration is 4.5 kW. Due to suddenly increment in required power at t=5, fuel cell output voltage which was the 30 V decreases 28 V. However at this time current increases to 192 A.

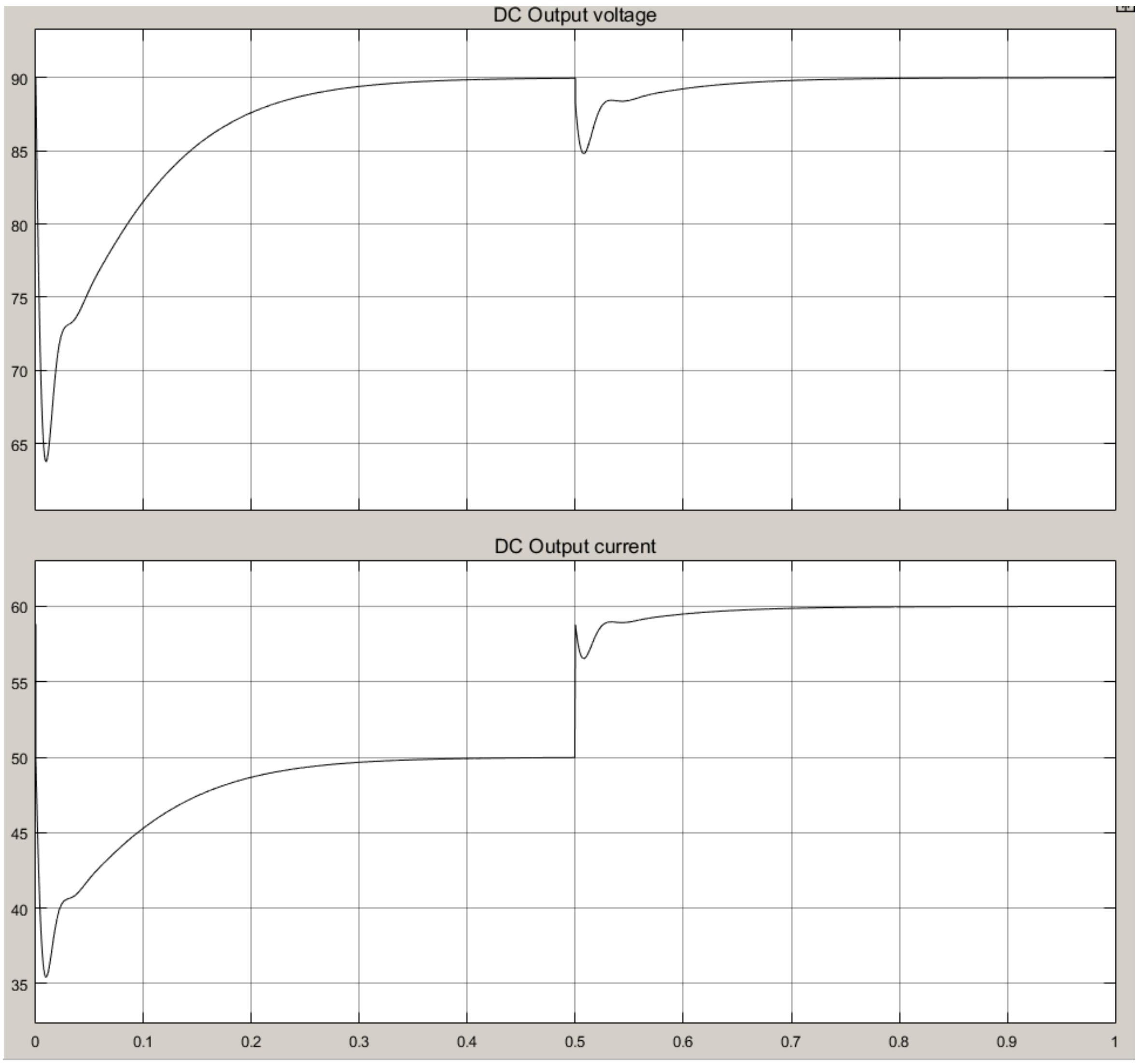

Figure 8.9: Output current and voltage of converter at t=5 increase load

Despite of changing power at t=5 sec, thanks to using boost converter and its controller output voltage is protected. It’s illustrated in Figure 8.9.

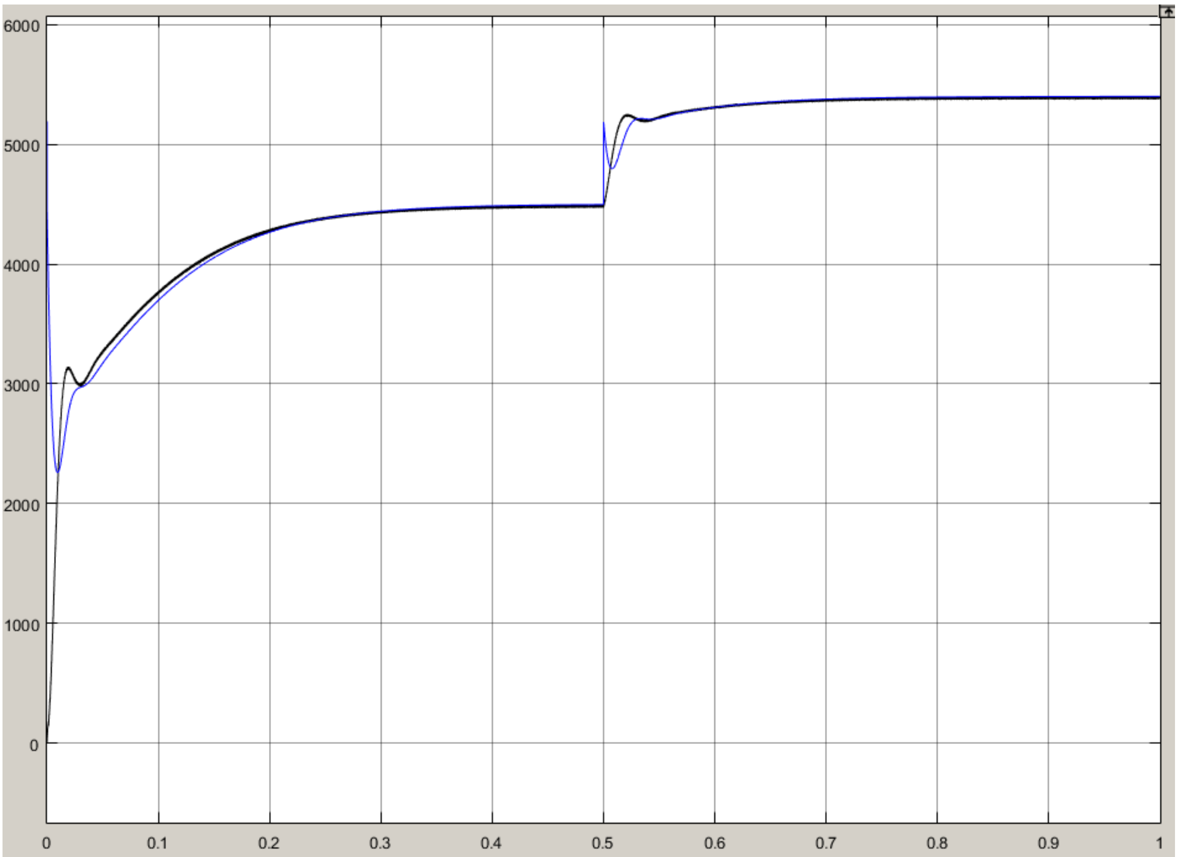

Figure 8.10: Output power and input power of converter

Figure 8.10 shows the output power and input power with capacitor. These are need for efficiency calculation. When added capacitor efficiency values increases.

Input Power= 5425

Output Power= 5400

$$ \text{ƞ} = P_o/P_i $$

$$ \text{ƞ} = 5400/5425 $$

$$ \text{ƞ} = \%99 $$

Figure 8.11 shows the efficiency of fuel cell stack. Fuel cell’s efficiency is around 52% while producing 4.5 kW power. 5.4 kW power is produced at t=5, for this reason efficiency decreases to 49%.

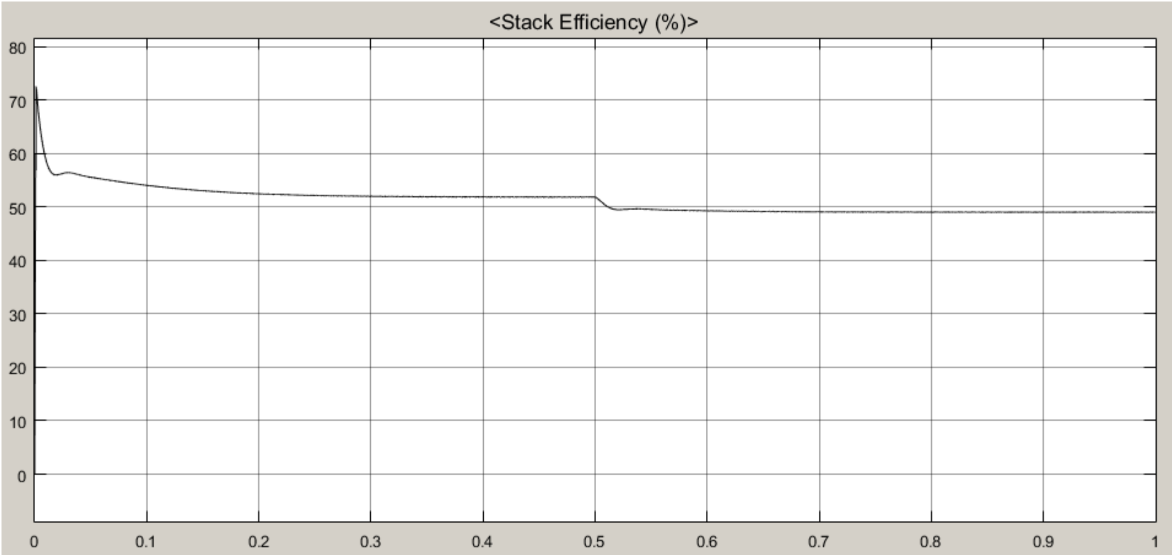

Figure 8.11: Efficiency of PEM Fuel Cell

CHAPTER 9

CONCLUSION

In this thesis, unmanned underwater vehicles and their power systems was given. Brief information about the types of batteries and their comparisons between each other that can be used in unmanned underwater vehicles was explained. Also, it's detailed that which types of fuel cell can be better suited to use for unmanned underwater vehicles, and which benefits will be gained if the fuel cell is integrated into the system. As a result of a detailed examination of the characteristics of the battery and the fuel cell, it was decided to integrate the fuel cell in the system instead of the battery.

In the scope of this thesis, the design of the autonomous underwater vehicle which operates with the fuel cell was simulated in Matlab Simulink environment. For this purpose, first a 4.5 KW PEMFC was designed in Matlab Simulink environment. Thereafter, a DC/DC boost converter was designed to step up the output voltage of the fuel cell. PI controller that controls the duty cycle is applied to the system so that the converter can deliver a constant voltage. All of these studies are simulated in the Matlab Simulink environment. The main purpose of integrating a fuel cell into an autonomous underwater vehicle is to reduce the weight of the underwater vehicle and to remove the time spent to charge the battery.

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