METHOD AND SYSTEM FOR SUSTAINABLE AND CLEAN HYDROGEN ENERGY USING WATER SPLITTING AND CONCENTRATED SUNLIGHT

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METHOD AND SYSTEM FOR SUSTAINABLE AND CLEAN HYDROGEN ENERGY USING WATER SPLITTING AND CONCENTRATED SUNLIGHT

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ABSTRACT

Hydrogen has the potential to become an alternative fuel to petrol or even electricity. For decades, approximately 95% of hydrogen consumed worldwide is produced from natural gas which is burned to produce heat required for chemical reaction or to generate electricity which in turn use to carry out electrolysis process. This process does pollution by releasing carbon dioxide to the environment. This thesis is focusing more on hydrogen production using environmental friendly resources, i.e. sunlight and water. Concentrated sunlight is a key component in producing heat required to either generate electricity for electrolysis processes, or drive the endothermic chemical reactions to split hydrogen and oxygen from water. Hydrogen produced can be directly use or be stored in the storage vessel for a continuous consumption via a controlled flow rate. A stabilize pressure control where hydrogen gas is evacuated is a key component in ensuring operability and stability of end user plant operation. This research project presents methodology available in controlling the pressure of hydrogen storage vessel. . A state space approach is adopted to mathematically model the hydrogen vessel storage pressure control application. In addition, a different set of modern controllers are introduced and the system response of each controller is investigated an analysed using MATLAB and Simulink tools. The advantages and limitation of each and every modern controllers are also discussed at length. The summary of result and the recommendations are also provided in this report as reference for readers.

ABSTRAK

Hidrogen berpotensi untuk menjadi sumber tenaga alternatif kepada petrol atau tenaga elektrik. Untuk sekian lama, kira-kira 95% hydrogen yang digunakan diseluruh dunia dihasilkan melalui sumber minyak dasar laut yang dibakar untuk menghasilkan haba yang digunakan bagi tindakbalas kimia atau haba untuk menjana elektrik yang digunakan oleh proses elektrolisis bagi menghasilkan hidrogen. Proses ini membebaskan karbondioksida yang menyumbang kepada pencemaran alam sekitar. Thesis in memperincikan bagaimana hidrogen boleh dihasilkan menggunakan sumber yang mesra alam sekitar, seperti air dan cahaya matahari. Sumber cahaya matahari adalah komponen utama dalam menghasilkan tenaga haba yang boleh digunakan untuk menjana elektrik bagi proses elektrolisis ataupun haba yang digunakan untuk memacu proses tindakbalas kimia untuk memisahkan molekul hydrogen dan oksigen dari sumber air. Hidrogen yang dihasilkan boleh digunakan terus atau disimpan dalam kebuk simpanan yang dikawal tekanan pengalirannya bagi kegunaan yang berterusan. Tekanan yang stabil didalam kebuk simpanan memastikan loji dapat diurus dengan stabil dann cekap. Pendekatan kawalan *state-space* digunakan untuk menghasil model matematik kebuk simpanan hydrogen. Beberapa system kawalan moden diperkenalkan dan setiap rekabentuk, kebaikan dan kelemahaan prestasi dianalisa dan dibincangkan dengan terperinci. Rumusaan kepada semua penemuan yang dibincangkan dibuat pada penghujujng laporan projek kajian ini.

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LIST OF SYMBOLS AND ABBREVIATIONS

B	:	Viscous-friction coefficient
CH_4	:	Methane
CO_2	:	Carbon dioxide
CSP	:	Concentrated Solar Power
DC	:	Direct Current
EMF	:	Electro Motive Force
H_2	:	Hydrogen
H_2O	:	Water
HI	:	Hydroiodic Acid
HTF	:	Heat Transfer Fluid
$i_a(t)$	:	Armature current
J	:	Moment of Inertia
K_a	:	Torque constant. Product of $K_m.\Phi_f$
K_b	:	Proportionality constant
K_b	:	Control valve coefficient
K_m	:	Motor parameter
MWe	:	Mega Watt electric
O_2	:	Oxygen
P	:	Pressure
PID	:	Proportional Integral Derivative
PTC	:	Parabolic Through Collector
Q	:	Mass flow rate
SI	:	Sulfur Iodine
T_m	:	Motor torque

V	:	Voltage
V_b	:	Back E.M.F
Zn	:	Zinc
ZnO	:	Zinc Oxide
θ	:	Angular rotation
α	:	Proportional
Φ_f	:	Field flux
ω	:	Angular rotation of motor

CHAPTER 1: INTRODUCTION

1.1 Overview

Hydrogen is by far regarded as a clean fuel such that when it get burned, produces water vapor as the only exhaust product. However, it is not an energy source that is readily available for immediate use. Despite it being the most abundant element in the universe, it is usually stored in substance like water, natural gas i.e. methane, and other living matter. Being able to efficiently extract it from those substances is a key to, as well as a challenge of using hydrogen as an alternative energy source.

Water, coal, natural gas or biomass are a few example where hydrogen can be extracted from. As of to date, natural gas particularly methane compound which goes through the process called steam methane reforming is the common method of producing hydrogen**.** This process however contribute to climate change and air pollution by releasing CO_2 as carbon emission to the environment. As the world struggle to eliminate or at least reduce the dependency on natural gas, alternative to producing hydrogen with renewable energy sources and environmental-friendly substance such as water provide a path to building a sustainable energy system. At present, automotive companies like Honda, Toyota and Mercedez Benz are increasingly investing in hydrogen fuel cells, as it is both cheaper and better for the environment.

Clean hydrogen production shall be based on water and energy from renewable resources. Solar electricity generated by concentrated sunlight, and followed by electrolysis of water, is a feasible route to producing hydrogen. Water splitting technique employing endothermic chemical reaction to separate hydrogen and oxygen is another viable routes of producing hydrogen, and becoming a subject of intense research and development by many institute and organisation. The endothermic chemical reactions involved in the process makes use of concentrated solar radiation as the source of high temperature heat (Meier & Sattler, 2009) . However, as oppose to electrolysis, thermochemical processes require higher temperature which would require massive investment in term of solar field facilities and overall cost of plant operation.

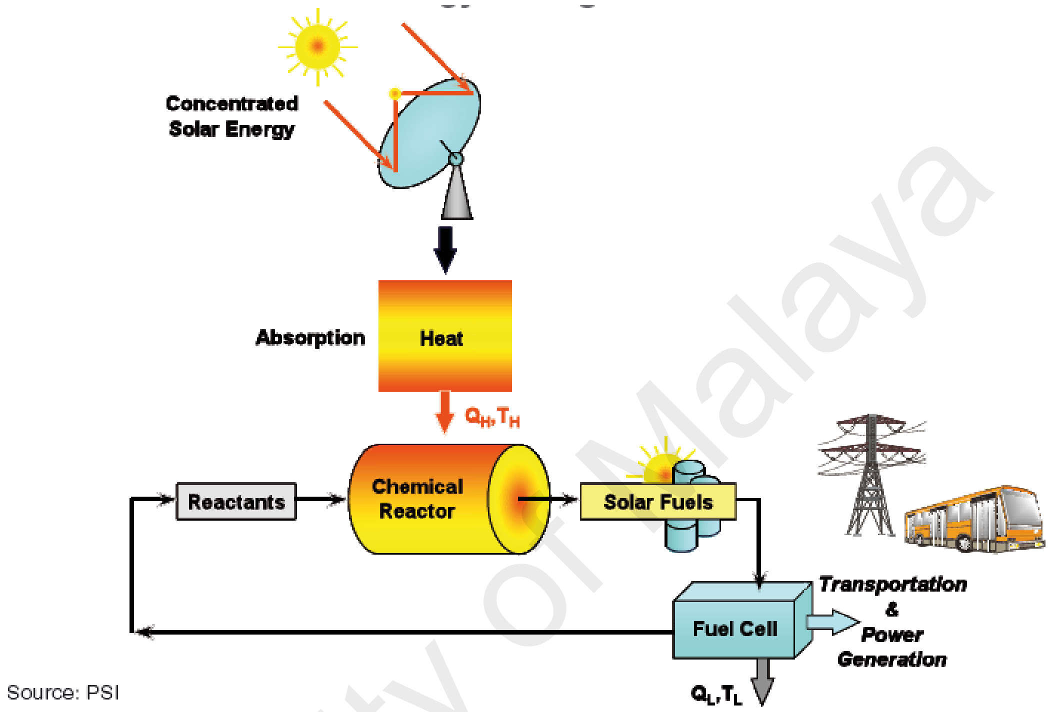

Figure 1.1: Energy conversion into solar fuels

One of the challenges when it comes to using solar as a primary source of energy lies in the nature of solar radiation i.e. it is intermittent, hence a form of storage is deemed necessary. Conversion of sunlight energy into chemical fuels is an attractive approach of solar energy storage. Figure 1.1 shows how hydrogen is being produced via chemical reactor which make use of concentrated sunlight as a source of heat, which will be then stored in a storage vessel to be further processed into mechanical work by steam turbine or use directly by fuel cell to generate electricity. Therefore, some kind of control is required to ensure that hydrogen is consumed at a controlled rate so as not to interrupt the end user plant operation.

1.2 Objective

This research project aims to explore the method and system available to producing clean hydrogen via water splitting and concentrated solar energy. Apart from that, the following are what this research project aims to achieve:

1. Identify available and different routes for producing clean hydrogen, or well known as solar fuel, from water and solar energy.
2. In addition, it seeks to explore the controllability part of hydrogen energy storage particularly using modern control approach. The approach will be via developing mathematical model of the system combining with computer simulation.
3. Employing different type of modern controller and comparing the advantages and disadvantages against one another.
4. To eventually recommend a suitable modern controller to be adopted by the system.

1.3 Scope and Limitations

The scope and limitations of the research project are:-

1. Limited to method and technology available to produce hydrogen via water splitting technique. Though other method of generating energy and heat such as nuclear reactor and photovoltaic are available, the focus is given to the concentrated solar power.
2. Only hydrogen storage section is considered to be part of the modern control analysis and simulation.
3. No hardware or prototype is expected to be built. Only computer model and simulated controller is expected to be derived from this work.

1.3 Research project outline

This report is divided into five (5) chapters as per following:

Chapter 1: Introduction – includes introduction to methods and systems available to producing clean hydrogen from concentrated sunlight.

Chapter 2: Literature Review – a review on research materials in relation to hydrogen production via water splitting and how concentrated sunlight can be leveraged together with water splitting technique to produce hydrogen. Also the method of storing the hydrogen for end-user use.

Chapter 3 – Methodology - describes the technique of controlling the hydrogen pressure supply vessel to the end-user or consumer. This chapter explains simulation methodology being carried out using MATLAB software to model the pressure control system of the hydrogen storage vessel. Different type of modern controllers and their inherent limitation and suggestion for improvement will be explained.

Chapter 4: Results & Discussions – the results obtained from the simulation exercise conducted in Chapter 3 will be discussed in great detail.

Chapter 5: Conclusion – the overall research will be concluded with some recommendation for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Hydrogen is not an energy source that is readily available for immediate use. Despite it being the most abundant element in the universe, it is usually stored in substance like water, natural gas i.e. methane, and other living matter. It takes considerable amount of energy from an energy source, such as electricity, chemical reaction processes or high temperature sources such as nuclear reactor and concentrated solar energy to produce hydrogen. Hydrogen can be burned to generate heat, further processed into mechanical work by generator and turbine, or be used to produce electricity directly within fuel cells.

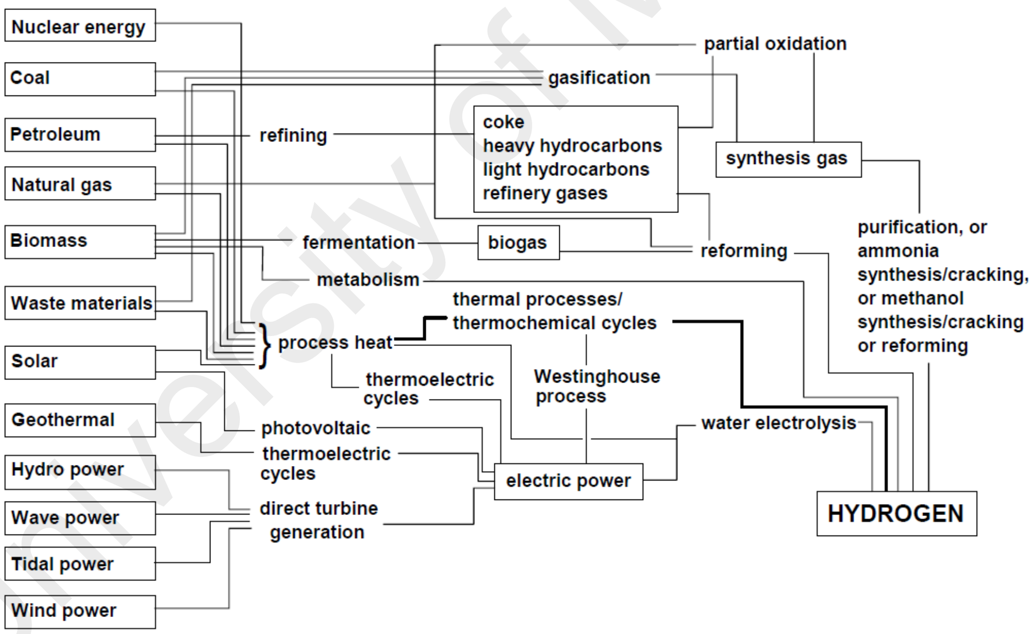

Figure 2.1: Link between primary energy sources used to produce hydrogen

Various routes to hydrogen production with their respective primary energy sources are illustrated in Figure 2.1 (Hinkley et al., 2006). In the early days, hydrogen was produced using coal thru gasification processes or heat generated from burning the coal. It was the subject of debate particularly among environmentalist as it pollutes environment as a result of coal mining activities as well from the heat generation plant. As of to date, the common method of producing hydrogen is by using natural gas i.e. fossil fuel, via a high temperature process called steam methane reforming.

Hydrogen is produced by using high temperature steam, ranging from 700 to 1000 °C, under 300 to 2,500 KPa pressure which react with natural gas contains methane (CH_4), along with the presence of a catalyst. A fair amount of carbon monoxide is also produced as a by-product. The steam-methane reforming reaction can be represented as:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Nickel or nickel based alloys are generally used as catalysts. Subsequently, the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen (Real, 2019). The water-gas shift reaction can be represented as:

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+ small amount of heat)}$$

The overall reaction can then be represented as:

$$CH_4 + 2H_2O + \text{thermal energy} \rightarrow 4H_2 + CO_2$$

The steam generated in the chemical reaction processes to produce hydrogen is mainly generated from the fossil fuel. This produces greenhouse gases that pollutes the environment. As the world struggles to eliminate or at least reduce the dependency on fossil fuels, it opens up the opportunity of exploring different methods and technology of producing hydrogen from renewable energy sources. Clean hydrogen production shall be based on water and energy from renewable resources such as solar radiation, wind, water currents, tides and waves.

Various technical routes to clean hydrogen production are available such as electro-chemical process which uses electricity generated from renewable resources followed by electrolysis of water. Thermochemical route uses heat from concentrated sunlight which will then be consumed by endothermic chemical reaction to split hydrogen and oxygen from water. Photochemical or photo-biological route on the other hand makes direct use of solar photon energy for photochemical and photo-biological processes respectively to produce hydrogen from water (Meier & Sattler, 2009).

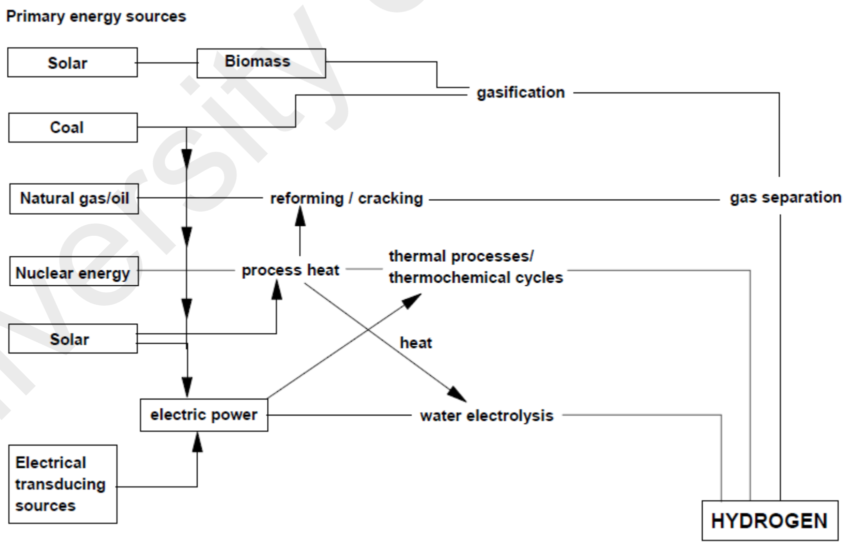

Figure 2.2: High temperature processes for production of hydrogen

Solar thermal processes illustrated in Figure 2.2 demonstrates the range of possibilities for hydrogen production which exploits intensity of solar radiation to either generate process heat which will then be used in thermal processes/ thermochemical cycles or generate electricity via solar concentrated power or photovoltaic cell followed by water electrolysis (Hinkley et al., 2006).

The next section of this research project report will discuss a bit in detail of how solar radiation is exploited to generate electricity which will then be used by electrolysis process, or generate heat which is consumed by endothermic chemical reaction to produce clean hydrogen.

2.2 Sunlight Concentrating System

Sunlight is by far the most abundant carbon-neutral energy resources on earth. More energy from the sunlight strikes the earth in one hour than it is consumed by all fossil fuel in one year(Meier & Sattler, 2009). Figure 2.3 shows the amount of solar radiance across continents on earth. Those area closer to equator typically have greater annual solar radiance than those in the north or south of the globe. For instance, Malaysia has an average of 5kWh/m^2 compared to Russia which have average solar radiance of less than 2.0 5kWh/m^2 (Energy, 2016)

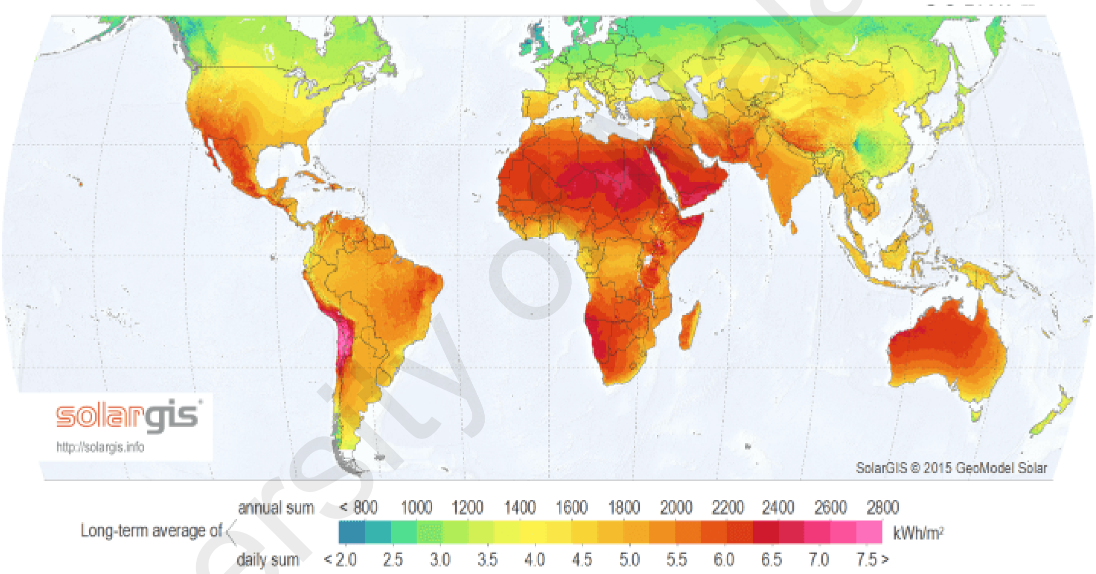

Figure 2.3: Annual solar energy potential on earth

Concentrated solar power (CSP) focuses on harvesting the solar energy which generates greater solar power by using large number of reflecting materials which collect sunlight and focus onto a small area. The resultant process generates solar thermal energy which can be used to produce electricity or drives the thermochemical endothermic reactions processes.

However, solar energy - by nature, is an intermittent source that can vary significantly within the day, week or even within a year. In order for it to be a primary energy supply, the capture and storage of solar irradiance energy is necessary and must be made effective. Figure 2.4 shows several solar concentrating system such as (a) parabolic trough collectors, (b) solar tower, (c) parabolic solar dish and (d) double concentration system (Kodama, 2003).

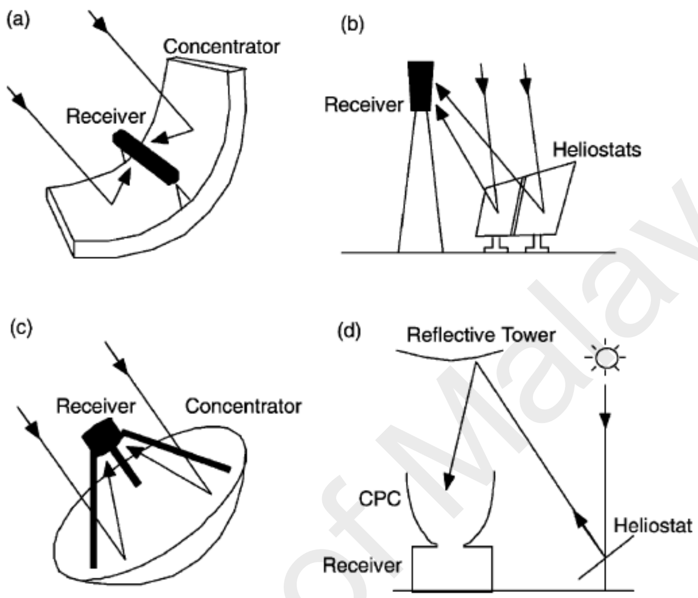

Figure 2.4: Different concept of solar concentrating system

Among them, the parabolic trough solar collector (PTC) and solar power tower (SPT) are considered technically viable technology used commercially by power generation plant and industrial process heat plant. The technology has caught attention of many researchers worldwide and has a great potential to replace current method of producing energy (Zhang, Baeyens, Degrève, & Cacères, 2013). The following sub-section seeks to explore more about the application, limitation and future direction of PTC and SPT respectively.

2.2.1 Parabolic Trough Collector System

Parabolic trough collector (PTC) is the most established solar concentrating technology worldwide. A PTC is a line-focus concentrator which converts concentrated solar energy into high-temperature heat. Depending on the application, temperature up to 550 °C is achievable with this system (Tian & Zhao, 2013) . The key component of the conventional PTC is a concentrator of linear parabolic shape, a tubular receiver and a metal support structure.

The receiver of the conventional PTC is an evacuated tube receiver with a metallic inner tube and an outer glass tube. Usually, the outer surface of the absorber has a selective coating in order to reduce the radiation thermal losses to the environment. (Duffie & Beckman, 2013*)*. Figure 2.5 shows conventional PVC with linear parabolic shape concentrator, a tubular receiver where fluid is passing thru and a metallic structural frame that holds the setup.

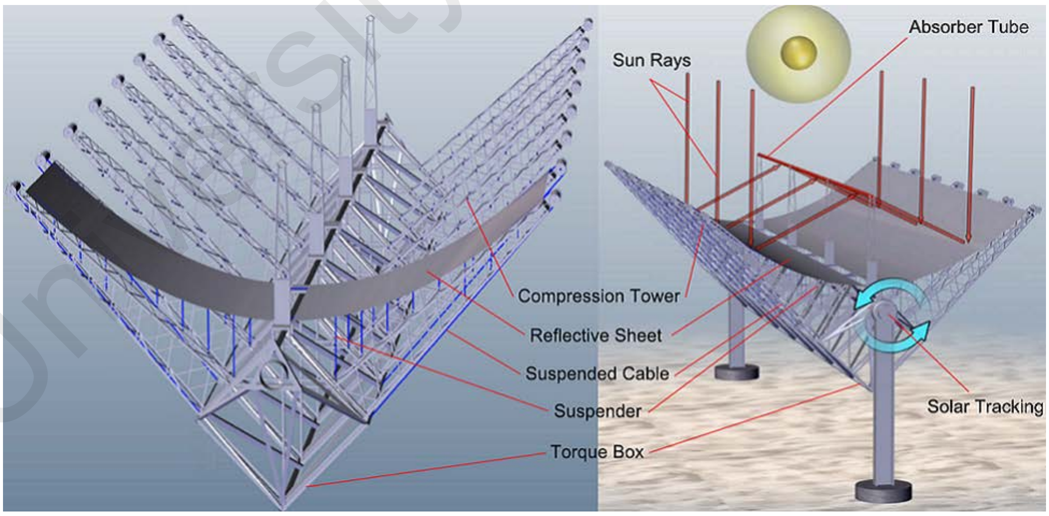

Figure 2.5: Typical PTC structure

Typically, the PTC is separated into modules and many modules are placed linearly in series. A number of series are arranged in a parallel and they make up of the total solar field. Depending on the configuration, the module can have a length close to 10 meter and every series has approximately ten to twenty modules. A single axis mechanism is usually used to tracks the sun in order for the sunlight to be distributed properly in the collector aperture.

Figure 2.6: Row of PTC arranged in parallel

Figure 2.6 shows row of parabolic trough solar collector arranged in parallel, in a concentrated solar power plant located in Kuraymat, Egypt. The plant has the total solar aperture area of 130,800 m2. A layout model of the use of PTC in concentrated solar power plant is illustrated in Figure 2.7. This plant comprises three main blocks, namely the solar field, thermal energy storage and power block. Solar field consists of assembly of receiver tubes containing the heat transfer fluid and parabolic reflector which focusses solar radiations onto the tube.

Synthetic oil is typically used as a medium that absorbs heat from solar radiation. However, as the price of synthetic oil is high, molten salt which is known as material that can preserve heat for a longer period of time, provides alternative to the synthetic oil.

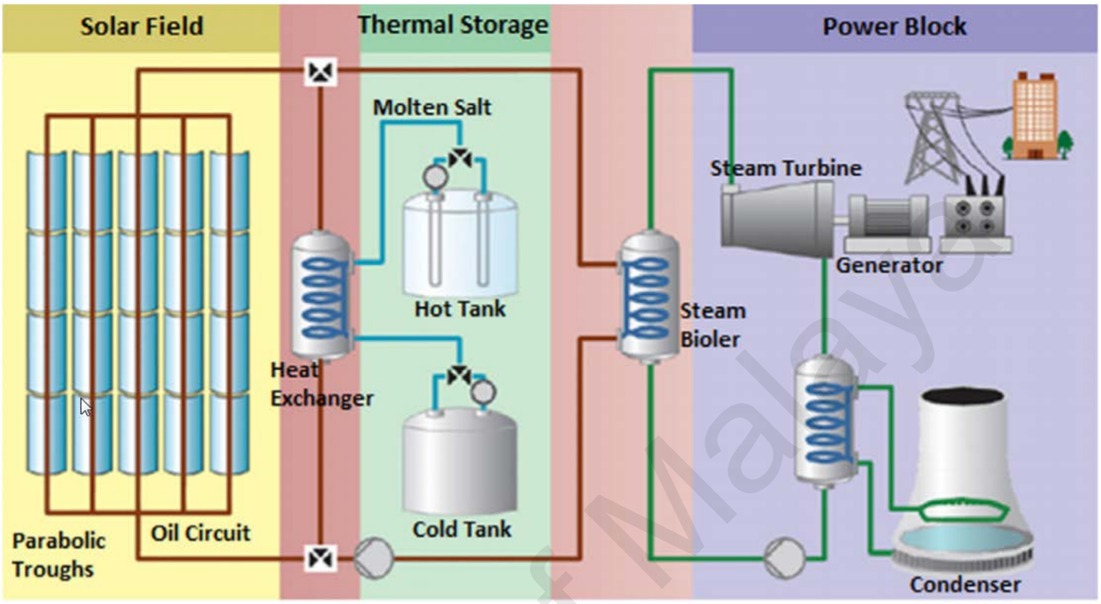

Figure 2.7: PTC concentrated solar power plant layout

This setup has another advantage apart from being cost effective. Thermal energy storage consists of two tanks i.e. cold tank and hot tank. Cold tank serves as a storage for molten salt in the form of solid. When molten salt is subjected to a temperature of 200 °C or higher, it melts and becomes liquid. In the daytime when high solar energy is available, molten salt absorbs the excess heat energy and stored it in the hot tank, which is well insulated to minimize thermal losses to the environment.

In the night time, the hot molten salt transfers its heat to the synthetic oil through the intermediate heat exchanger and the low-temperature molten salt at the outlet of the heat exchanger is transferred to the cold tank. The hot synthetic oil then transfers its heat to water in the steam boiler heat exchanger to produce high pressure steams to rotate the steam turbine. The exhausted steam from the steam turbine is condensed to water in the condenser to shift it back to the boiler to complete the close cycle. (Awan, Zubair, Praveen, & Bhatti, 2019). Hot molten salts serves very much like a battery that will ensure continuity of the plant in the absent of solar radiation.

2.2.2 Solar Power Tower

Solar power tower (SPT) works very much the same way with parabolic through collector system (PTC) except that instead of using parabolic concentrator, it uses a significant number of sun-tracking mirrors called heliostats to focus sunlight onto a tubular receiver mounted at the top of a tower. Figure 2.8 illustrates the typical setup of solar power tower with heliostat and tower with tubular receiver which make up the solar field, molten salt that serves as thermal storage energy and power block which transfer the heat into practical use that is electricity.

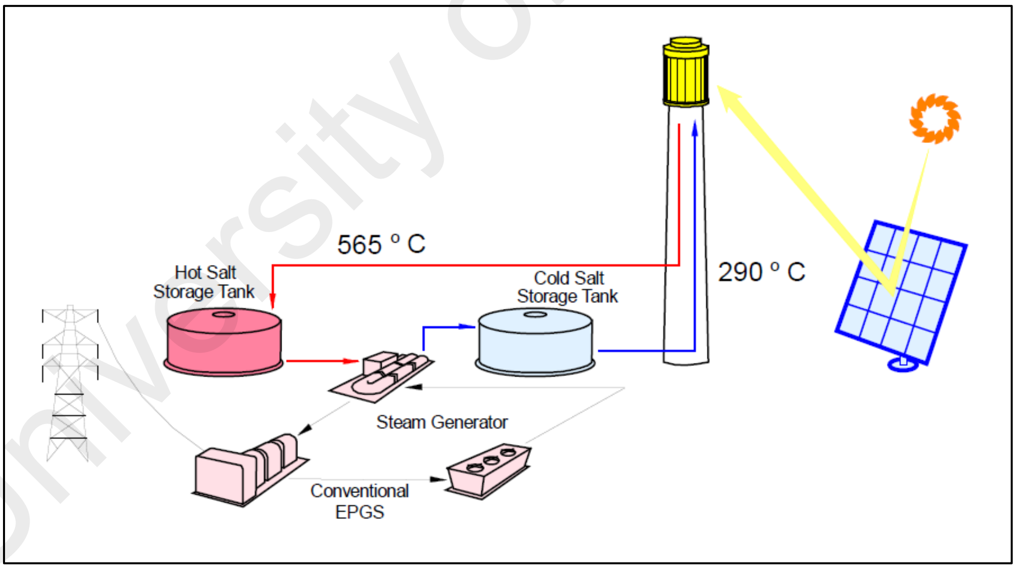

Figure 2.8: Schematic of Solar Power Tower with thermal energy storage

A large number of heliostat tracks the sun and reflects the light onto a central receiver mounted on top of the tower throughout the day. Figure 2.9 shows an array of heliostat, amounting to 2,000 units installaed in Solar-2 facilities in California, United State of America (Allison, 2017). The central receiver shown in Figure 2.10 typically made up of variable number of vertical blocks of tubes, which allow the passage of heat transfer fluid (HTF) to flow through it.

Figure 2.9: Heliostat array located in California

The concentrated sunlight collected by the heliostat field is used to heat up the HTF to approximately 565 $^{\circ}$C, then it flows to the thermal storage (Kolb & J, 2011). HTF, which is typically of a molten salt is extracted from the storage system to where the heat is transferred to water to produce steam which in turn drive the steam turbine electric generator. Given the nature where it operates and exposed to, tubular receiver must be of high temperature material class, superior to corrosion and most importantly be resistant to thermal stresses and fatigue due to the solar flux transient (Rodríguez-Sánchez, Sánchez-González, Marugán-Cruz, & Santana, 2014).

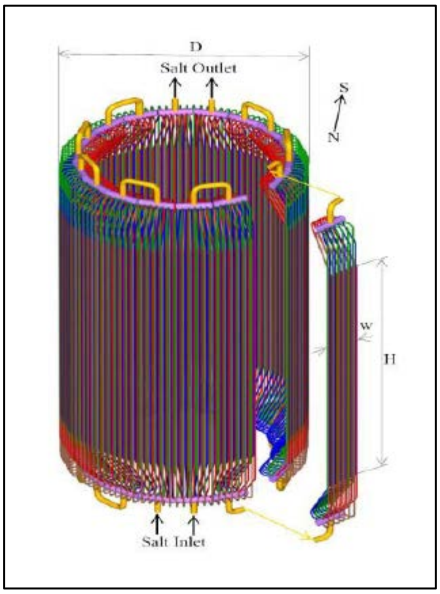

Figure 2.10: Schematic of conventional external receiver mounted on top of tower

SANDIA report suggests that over the past 20 years, there has been a growing interest in concentrating solar power tower technologies, which offer high efficiency and opportunity for a low cost electricity. Abengoa's PS10 (11 MWe) and PS20 (20 MWe) steam towers in Spain and eSolar's Sierra SunTower (5MWe) steam towers in California are among commercial electric power plant which employ this type of technology. A roadmap has been developed to look at ways and cost reduction measures available to achieve large-scale deployment of solar concentrating power technologies (Kolb, Ho, R Mancini, & Gary, 2010).

2.3 Hydrogen from Water-Splitting

While today hydrogen is predominately generated from the processing of fossil fuels, which as a by-product results in the release of CO_2, there is already a promising technology and a great deal of research being carried out to produce hydrogen by splitting of the water molecule that do not necessarily, result in the emission of greenhouse gasses. Amongst the technology available are listed down below (Grimes, Varghese, & Ranjan, 2008) :

i. Water electrolysis
ii. Water biophotlysis
iii. Thermochemical cycles
iv. Mechano-catalytic
v. Water plasmolysis
vi. Water magnetolysis
vii. Water radiolysis

Figure 2.11 shows a promising routes to producing hydrogen with water-splitting technique. Hydrogen production via electro-chemical i.e. source of electricity followed by electrolysis of water, solar thermolysis and solar thermo-chemical cycles are three major routes which are gaining much attention at present time. This will be described a bit in detail in the next sub-section. The rest of the available technology are briefly described below.

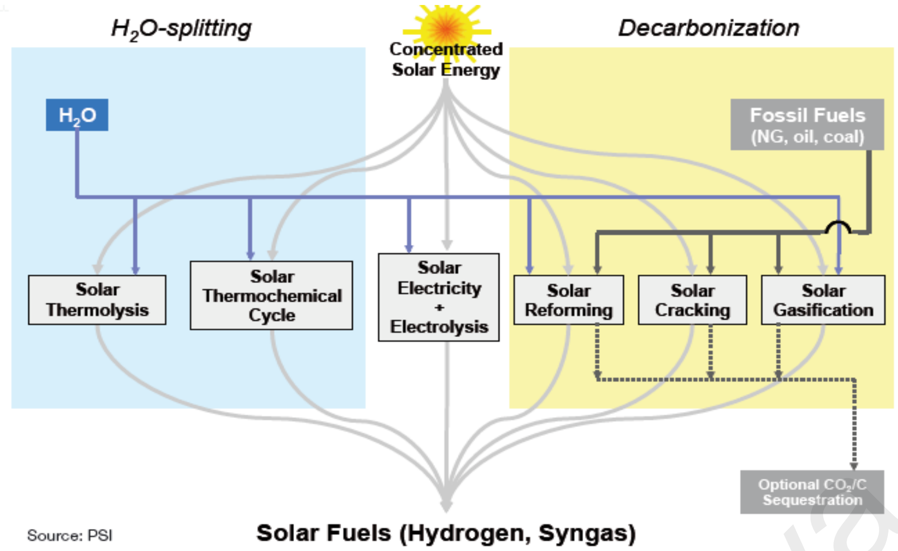

Figure 2.11: Various routes for solar hydrogen production

Mechano-catalytic is employing mechanical energy applied to agitate the distilled water which has been poured with catalyst i.e. oxide powders to decompose water into hydrogen and oxygen (Takata et al., 2000). Water plasmolysis involves the process of water splitting using electrical discharge. Electrical generation of the plasma causes ionization, dissociation and excitation of molecules and atoms. Water is sprayed through a plasma created in reactor where the thermodynamically reaction take place to release hydrogen (Bockris, Dandapani, Cocke, & Ghoroghchian, 1985). Magnetolysis is essentially electrolysis which uses magnetic induction to generate the needed voltage inside the electrolyser. Radiolysis of water involves the use of radioactive materials and highly energetic particles for water decomposition. (Grimes et al., 2008).

2.3.2 Hydrogen production by water electrolysis

Electrolysis of water to generate hydrogen and oxygen is an old and developed technology, and has a history of more than two centuries (Kreuter & Hofmann, 1998). Hydrogen production via water electrolyser constitutes approximately 3.9% of the world annual demand (Ewan & Allen, 2005). It generally uses electricity generated from the power station, which is not really an environmental friendly source of energy. Renewable energy such as solar concentrated power, wind turbine and solar photovoltaic provide alternative energy source with no emission of greenhouse gasses.

Alkaline electrolysis

The discovery of electrolytical water splitting was first made in acidic water, but due to its inferiority towards corrosion, alkaline has been the preferred medium because corrosion can easily be controlled with cheaper construction materials (Kreuter & Hofmann, 1998). Alkaline electrolyser is typically made up of cell frame, electrolyte, anode, cathode and a separator. The cell frame is generally constructed from the stainless steel, or a superior material titanium plates (Shiva Kumar & Himabindu, 2019). It is important to note that pure water is a poor ionic conductor hence it is hardly used as electrolyte. The electrolyte should provide high ion conductivity with the addition of alkalis, like aqueous sodium hydroxide or potassium hydroxide.

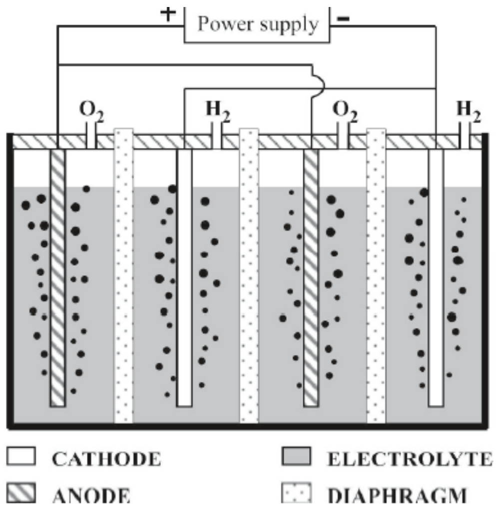

Figure 2.12: Two-cell conventional alkaline electrolyser

Figure 2.12 shows typical setup of conventional alkaline electrolyser. The electrodes are made of electro catalytic materials to ensure low overvoltage by facilitating rapid electrode-electrolyte charge transfer, and nucleation of gas bubbles at the electrode surface as well as their self-detachment from the electrode surface at the operating cell voltage. Nickel, cobalt and stainless steel are typically used as electrodes. Porous diaphragm-like separator are used to separate the anode and cathode. This is important to prevent mixing of liberated hydrogen and oxygen whilst still allowing for passage of electrolyte solution. The pore of the diaphragm should typically be smaller than the diameter of smallest gas bubble, that is around 10µm. Common materials use as diaphragms are asbestos, woven cloth, polymer materials like NiO and cermets like Ni-$BaTio_3$ (Grimes et al., 2008).

Hydrogen releases take place at the cathode, and oxygen evolution takes place at the anode. The alkaline electrolyser generally require relatively simple construction, low cost, and are easy to maintain. However it is huge in scale and cannot be operated at high temperature (typical operating temperature between 60 to 90 °C). In addition, as pure water cannot be used directly as an electrolyte, there are environmental concerns related to the chemical added into the water to produce electrolyte.

Solid Polymer Electrolyser

Another type of electrolyser, which is solid polymer electrolyser, or also known as membrane analyser, offers better alternative to the typical water analyser with electrolyte. Pure water can be used directly without having to add acids or alkalis. The development of solid polymer electrolyte along with the invention of proton exchange membrane fuel cells has made it to become industrial well-accepted technology. Figure 2.13 illustrates the physical construction of solid polymer electrolyser.

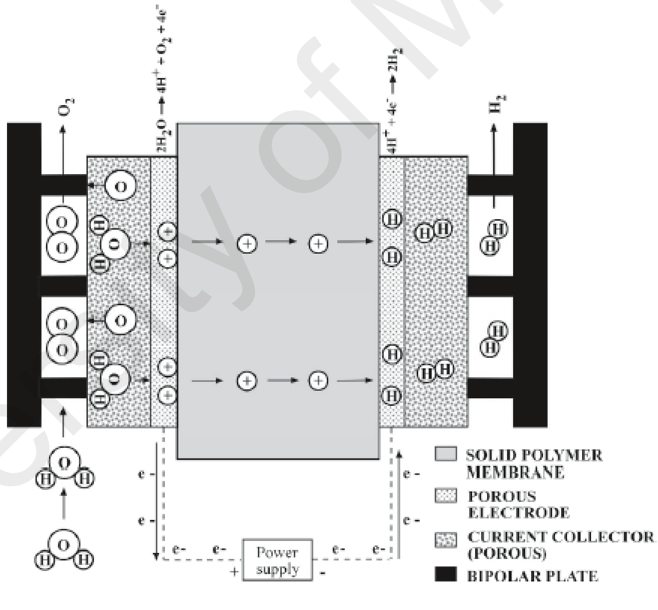

Figure 2.13: A solid polymer electrolyser configuration

Pure water introduced and circulated through the cell is split into hydrogen and oxygen with the help of electro-catalyst on the membrane surface. The bipolar plates, which is typically made of titanium, are connected to the porous structure that separate adjacent cell while allowing current to pass from one cell to the next. Porous electrode, which is normally made of titanium or carbon for anode and cathode respectively, provides exit paths for the gas generated at the electrodes(Grimes et al., 2008).

As opposed to alkaline electrolyser, solid polymer electrolyser are more efficient, reliable and safer. It allows direct use of pure water without having to add acids or alkalis which is the source of environmental concerns. However, it is relatively expensive owing to the high cost of polymer membrane and superior materials required for the electrodes. Other than that, the precise control of differential pressure between anode and cathode is of paramount important to ensure the effectiveness of this technology (LeRoy, 1983).

Solid Oxide Electrolyser

Solid oxide electrolyte is another emerging technology for hydrogen production through water electrolysis. The cell can operate at high temperature, nearly 1000 °C which liberates hydrogen from steam instead of pure water. The total energy demand for water splitting is lower in the vapor phase therefore electrical energy requirement are much lower (Grimes et al., 2008). Solid oxide electrolyte is fabricated in planar as well as tubular geometry. Figure 2.14 shows construction of tubular solid oxide electrolyser.

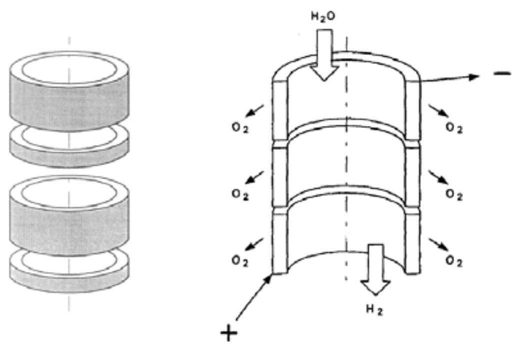

Figure 2.14: Construction of high temperature solid oxide electrolyser

The electrolyte is pressed between porous electrodes. The cells are attached in series using interconnecting elements that serve as electrical conductors as well as current distributors.

The feed gas in the form of steam is passed through the inner surface of the tube and oxygen is evolved through the outer surface.

Solid oxide electrolyser is still in the developmental stage. Material issues with regard to the high temperature operations is the hurdles that need to be resolved. Apart from that, the lifespan of materials used, intermixing of adjacent phases and engineering problem related to gas sealing are a few factors that prevent this technology from successful commercialization (Wendt, 1990).

2.3.3 Hydrogen production by thermolysis

Thermolysis involves relatively simple reaction to decompose water molecules into hydrogen and oxygen. The processes utilizes one-step thermal energy to dissociate hydrogen from water. The net reaction can be represented below:

$$H_2O + \text{thermal energy} \rightarrow H_2 + \tfrac{1}{2} O_2$$

Thermal energy in the form of heat above 2200 °C is required to accomplish a reasonable degree of dissociation. In addition, the effective method must be in place to separate hydrogen and oxygen to ensure that they are not intermixed that is to avoid ending up with explosive mixture. Among the early ideas proposed for separating hydrogen from water are effusion and electrolytic separation (Aldo Steinfeld, 2005).

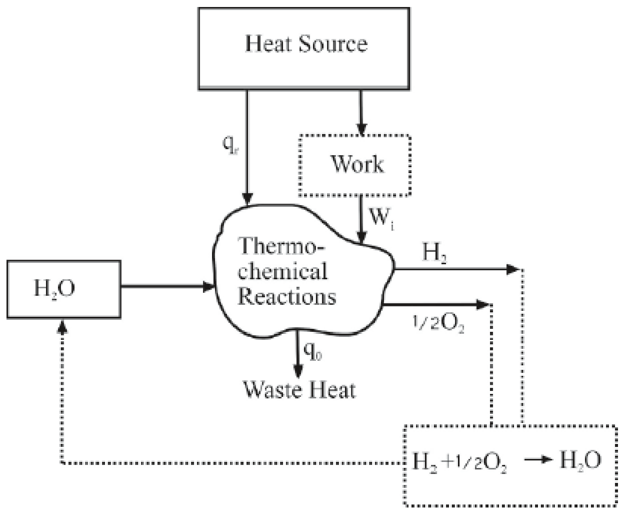

Figure 2.15: General representation of thermochemical water splitting process

The challenge is to find a suitable materials that can withstand very high temperate as well as capable of enduring chemically active environment within the reaction process. At present, theoretically, with such a high temperature requirement, the dissociation of hydrogen from water is slightly at over 4% at atmospheric pressure. Baykara explains that in order not to lose the small amount of hydrogen obtained, high temperature separation should take place in the reactor, as shown in Figure 2.15 above (Baykara, 2004).

It is apparent that a high-temperature process possess limitation to the materials as well as the effectiveness of reaction to split hydrogen and oxygen from water. At present the thermolysis is thought to be not economically attractive for commercial hydrogen production.

2.3.4 Hydrogen production by thermochemical-cycles

The inherent limitation of thermolysis can be improved by breaking down the reactions such that it goes through multi-step thermochemical processes before hydrogen is released. The most promising method developed thus far is the two-step processes involving metal and metal oxide that is Zn and ZnO.

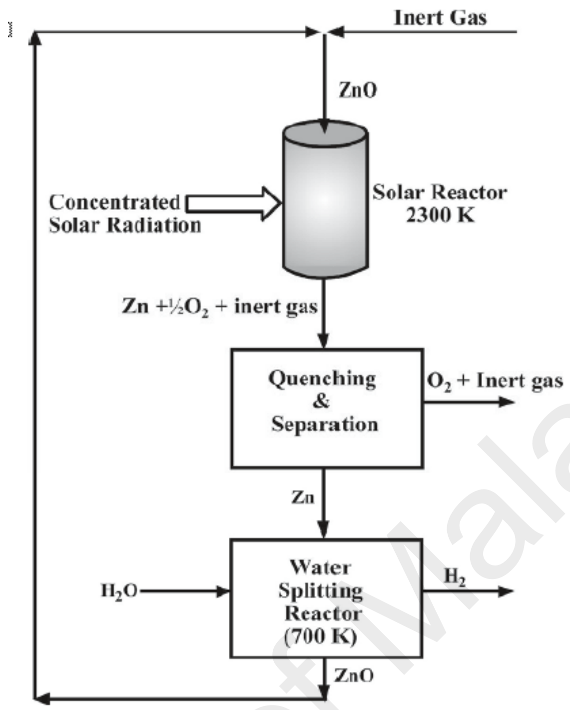

Figure 2.16: Process flow schematic of a two-step Zn/ZnO cycle.

Figure 2.16 shows the process flow schematic of two-cycle Zn/ZnO reaction cycle. Zinc oxide in solid or fine particle form is stored in a reactor cavity. This reactor cavity, typically made of materials like Inconel steel or silicon carbide is subjected to heat, at approximately 2026 °C which could be sourced from the solar concentrated power. This reaction causes the zinc oxide to dissociate to zinc and oxygen. The dissociation products are then cooled rapidly and transported to a low temperature zone using inert gas. Oxygen is then removed in this zone, leaving behind zinc in fine liquid or solid particulate form. The zinc is then going through water splitting reactor where steam is subjected to it, at approximately 426 °C, subsequently separating hydrogen and zinc naturally. The remaining zinc oxide is now available to begin the next cycle. Hydrogen and oxygen are evolved in different steps, thereby eradicating the need for high temperature separation (A. Steinfeld, 2002).

Sulfur-Iodine thermochemical cycle

However, the temperature regime used in two-step metal oxide process is still not low enough to enable large scale hydrogen production. An improvement to this method is multi-cycle processes with reasonable efficiencies are designed to overcome the limitation from the two-step thermochemical process. Sulfur-iodine cycle is one of the promising multi-cycle processes develop by General Atomic Corporation in middle of 1970s (Léde, Elorza, & Ferrer, 2001). Sulfur-Iodine cycle comprises of four different sections that is:

i. acid production and separation and oxygen purification,

ii. sulfuric acid concentration and decomposition

iii. Hydroiodic acid (HI) concentration

iv. HI decomposition and H_2 purification

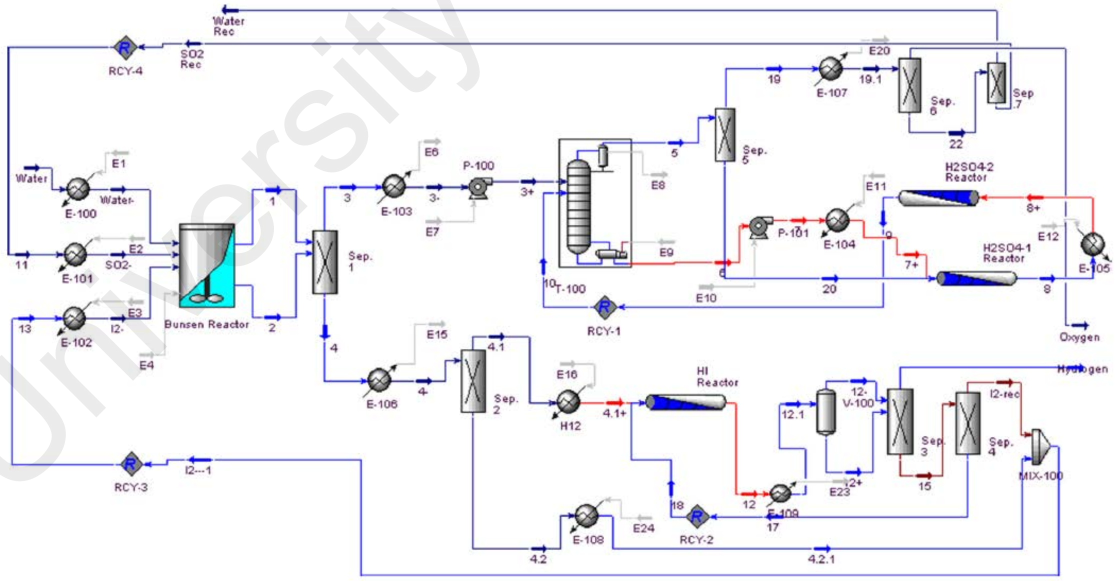

Figure 2.17: Simplified flow diagram for S-I process

Figure 2.17 shows simplified flow diagram for the sulfur-iodine thermochemical water splitting process. Initial section of cycle corresponds with Bunsen section, where water reacts with sulfur dioxide and iodin at approximately 120 °C, forming hydriodic acid and sulfuric. In the second section, the acid formed is then separated in the presence of a solid catalyst through an endothermic reaction, at a temperature ranging from 400 – 800 °C. Then it goes through third section where hydriodic acid is decomposed to form hydrogen and iodine. Pure hydrogen is then separated and iodine is reincorporated to the system at Bunsen section (García, González, García, García, & Brayner, 2013).

2.4 Hydrogen storage

A sustainable hydrogen production and consumption necessitate efficient and safe hydrocarbon storage and distribution. Hydrogen storage can be done physically, chemically and electrochemically (Kaur & Pal, 2019). Hydrogen being the lightest molecule, has very low density i.e. at 0.091 kg/m^3 at room temperature and atmospheric pressure. This literally means 1 kg of hydrogen gas occupies over 11 m^3 of storage area (Schlapbach & Züttel, 2001). There are different method of storing the hydrogen as illustrated in Figure 2.18, depending on interaction between gas molecule and the material used to store it.

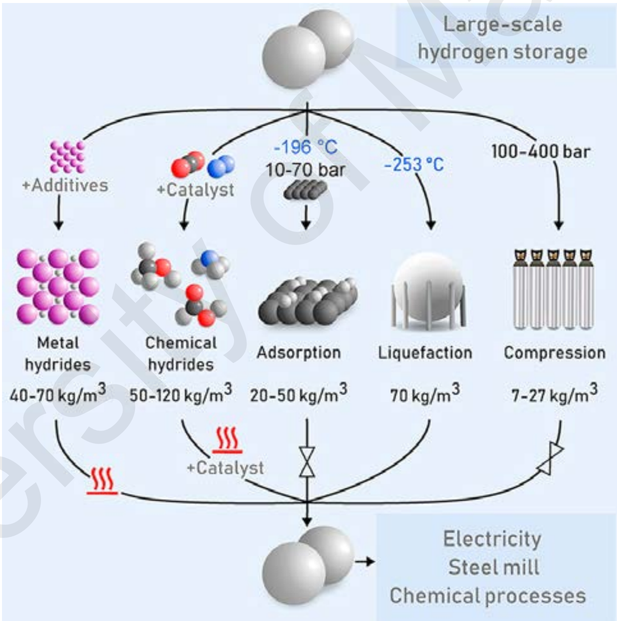

Figure 2.18: Categorization of hydrogen storage technologies

Hydrogen may be stored as a liquid or gas in its pure molecular form without any significant physical or chemical bonding to other materials. Apart from that, hydrogen molecule may be adsorbed onto or into a material, held by relatively weak physical van der Waals bonds. However, the adsorption process is exothermic which produces significant heat hence would be a challenge to manage (Ahluwalia, Peng, & Hua, 2015). As for the chemical hydrides method, hydrogen is chemically bonded to non-metallic elements such as carbon, nitrogen and boron whilst atomic hydrogen may also be chemically bonded to the metal atom. However, the drawback is that more energy is required to release the chemically bonded hydrogen (Andersson & Grönkvist, 2019).

Storage of hydrogen in its pure molecular form is the only type that are currently employed on a massive scale worldwide. The space industry and the large salt cavity storages in Texas, USA, and Teeside, UK among others are the apparent example of employing this method of hydrogen storage (Tietze, Luhr, & Stolten, 2016). It is therefore imperative that the hydrogen storage and its evacuation pressure is maintained at certain operating pressure to ensure smooth and uninterruptable daily operation.

CHAPTER 3: METHODOLOGY

3.1 Overview

This chapter highlights the research methodology employed to ensure the transfer operation of produced clean hydrogen gas to the end user is efficient and within well control environment. The sub-topic is focusing on the control of pressure of the hydrogen stored in the pressure vessel. The hydrogen is assumed to be continuously produced and consumed by the end user, hence stabile and precise control of pressure is of paramount important to avoid plant upset. The mathematical model is developed and the viability of it is tested and simulated using MATLAB Simulink software. A number of modern control approach is employed to evaluate the effectiveness of each and every control system.

3.2 Developing mathematical model

This research project presents the investigation of the control system for hydrogen storage system. It begins with defining the system to be controlled, by identifying the concept and developing the detail layout of the system, as can be seen in Figure 3.1 The next process involves developing functional block and schematic diagrams which illustrates multiple input variables exist in the system and the end goal i.e. the desired output, as shown in Figure 3.2. With the knowledge of multiple input variables, the relationship between input and output can be determined via psychical laws, such as Kirchoff's laws for electrical networks, Newton's laws for mechanical system and the law of conservation of energy. The relationship can be expressed mathematically and a transfer function of the system can be developed.

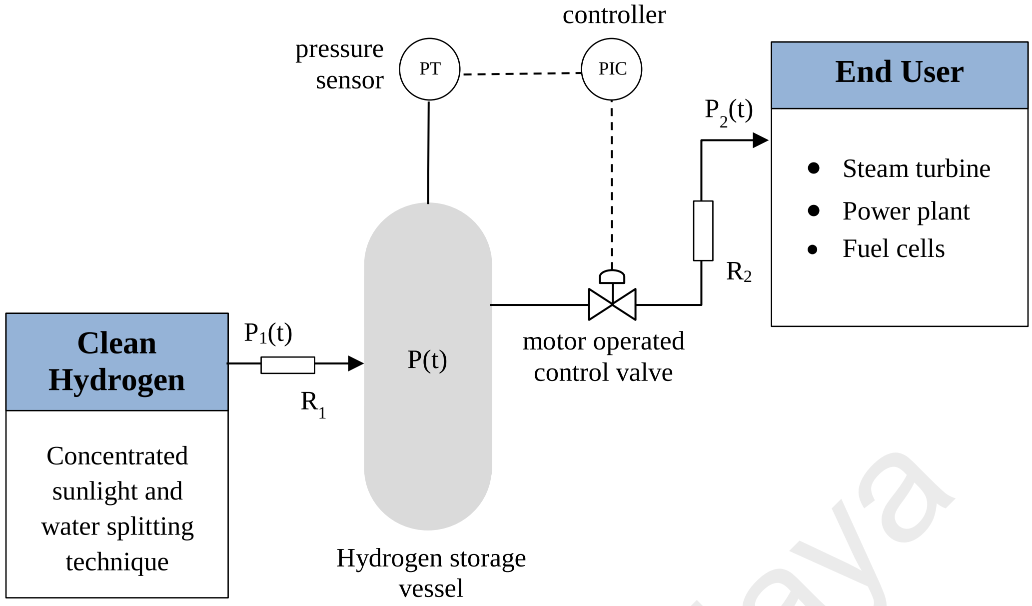

Figure 3.1: Schematic flow of hydrogen storage vessel

First Block

DC servo motor is used to drive the control valve from closed position to fully open position. Manipulating the control valve will ensure that the hydrogen storage vessel is kept at a desired pressure for a stabile operation. Linear characteristic control valve is chosen such that the complete rotational of servo motor from 0 – 360° corresponds to 0 – 100% travelling of the stem of control valve. The physical construction is depicted in Figure 3.3.

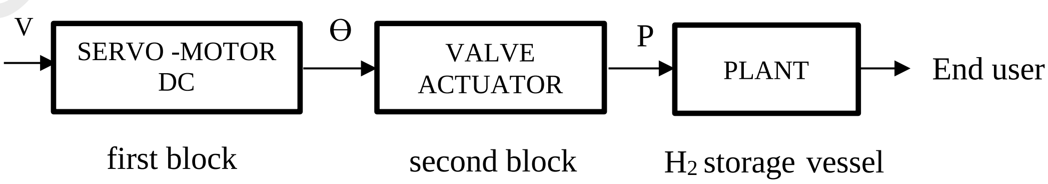

Figure 3.2: Functional block of pressure control station

The input to the system is the voltage applied to the motor's armature, while the output is the angular position of the shaft. The system variables are as follow:

V = Voltage supply to the armature winding

Ɵ = Angular position of servo motor DC that drive the linear position of the stem of control valve

P = Pressure of H_2 storage vessel

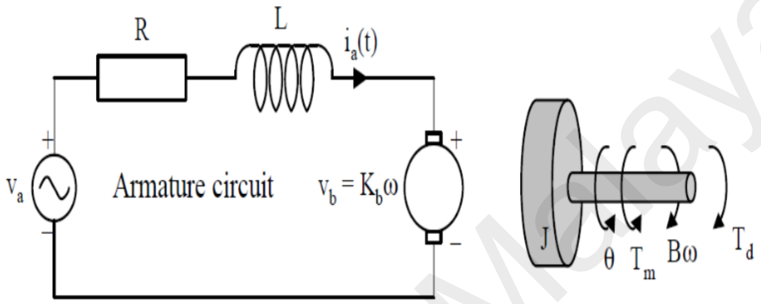

Figure 3.3: Physical construction of DC servo motor

Figure 3.3 shows equivalent electrical circuit of the DC servo motor. The following assumptions are made to derive the mathematical model:

1. Inductance L is too small that it is negligible
2. Armature current is constant
3. Torque α product of flux and armature’s current

Shaft torque used to drive load against inertia and frictional torque is given by:

$$T_m = J\frac{d^2}{dt}\theta + B\frac{d}{dt}\theta \quad (3.1)$$

The developed torque is also given as per assumption no. 3:

$$T_m = K_m.\Phi_f.i_a(t) = K_a.i_a(t) \tag{3.2}$$

Where,

T_m	=	Motor torque
J	=	Moment of Inertia (J)
θ	=	Angular rotation of the DC servomotor
B	=	Viscous-friction coefficient
K_m	=	Proportionality constant
Φ_f	=	Field flux
$i_a(t)$	=	Armature current
K_a	=	Torque constant. Product of $K_m.\Phi_f$

Back e.m.f of the DC servomotor is given by:

$$V_b = K_b\omega = K_b\frac{d}{dt}\theta \tag{3.3}$$

Where,

V_b	=	Back E.M.F
K_b	=	Proportionality constant

Applying Kirchhoff Voltage Law to the circuit in Figure 3.3 yields:

$$V_a = i_a(t).R + V_b \text{ or } V_a = i_a(t).R + K_b\frac{d}{dt}\theta(t) \tag{3.4}$$

Rearranging equation 3.4 to write $i_a(t)$ in term of V_a, R, K_b and θ

$$i_a(t) = \frac{V_a}{R} - \frac{K_b}{R} \cdot \frac{d\theta(t)}{dt} \tag{3.5}$$

Equating equation 3.1 to equation 3.2 yields:

$$T_m = J\frac{d^2}{dt}\theta(t) + B\frac{d}{dt}\theta(t) = K_a . i_a(t) \tag{3.6}$$

Substituting $i_a(t)$ from equation 3.5 yields into equation 3.6:

$$J\frac{d^2}{dt}\theta(t) + B\frac{d}{dt}\theta(t) = \frac{K_a}{R}(V_a - K_b\frac{d\theta}{dt}) \tag{3.7}$$

$$\frac{K_a}{R}V(S) = JS^2\theta(S) + \frac{BR + K_aK_b}{R}S\theta(S) \tag{3.8}$$

Rearranging equation 3.8 and applying Laplace transform, with zero initial condition

$$\frac{\theta(S)}{V(S)} = \frac{K_a/R}{JS^2 + \frac{BR + K_aK_b}{R}S} \tag{3.9}$$

Equation 3.9 is the transfer function of the first block, relating the angular rotation of servo motor to the input voltage applied to it.

Second Block

The process comprises of hydrogen produced using water splitting technique coupled with concentrated sunlight technology. Hydrogen gas produced is then stored in the pressure vessel where pressure is always maintained at approximately 5 barg, and subsequently evacuated for the end-user use and consumption. Figure 3.1 shows schematic flow of produced hydrogen, until the end cycle of the product. The inlet stream has flow Q_1 and pressure P_1. The outlet stream contains a control valve which serves to maintain the pressure of the hydrogen storage vessel. The outlet has a pressure P_2 and outlet flow Q_2 which would be intermittently fluctuating depending on the various demand of the end-user's plant. A dynamic model of the process is obtained from the component material balance under the following assumptions: -

1. The system considered is isotherm.
2. Flow resistance is linear.
3. Low pressure in the vessel.

Applying law of mass balance, if the inlet mass flow rate is greater than the outlet mass flow rate, hydrogen mass is accumulated over period of time in the vessel. Therefore the following equation can be written (Ahmed, 2008):

$$Q_{in}(t) - Q_{out}(t) = C\frac{dP(t)}{dt} \qquad (3.10)$$

Where C is the capacity of mass storage of the vessel.

Flowrate of mass is analogous to the current in electrical circuit. The flowrate is a function of differential pressure between two points, divided by the flow path resistance, which can be written as:

$$Q_{in}(t) = \frac{P_1 - P}{R_1} \qquad and \qquad Q_{in}(t) = \frac{P - P_2}{R_2} \tag{3.11}$$

Substituting equation 3.11 into equation 3.10 yields

$$\frac{P_1(t) - P(t)}{R_1} - \frac{P(t) - P_2(t)}{R_2} = C\frac{dP(t)}{dt} \tag{3.12}$$

Assuming that it is a lossless system where the pipe is frictionless, coupled with the short pipe distance between the source and the vessel, $P_1(t)$ can be approximated to $P(t)$, such that $P_1(t) \sim P(t)$. Equation 3.12 becomes:

$$C\frac{dP(t)}{dt} = \frac{P_2(t) - P(t)}{R_2} \tag{3.13}$$

As can be seen from Figure 3.1, if pressure in vessel $P(t)$ is hold constant, any movement or changes to the rod of control valve results in the changes in downstream pressure $P_2(t)$. The relationship can be written as:

$$P_2(t) = K_c . m(t) \tag{3.14}$$

Where $m(t)$ is the linear motion of the rod of control valve. As the valve is coupled to the servomotor gear, rotation of the motor shaft from 0 – 360° corresponds to the 0 – 100% opening of the control valve. Therefore $m(t) = \theta(t)$. Replacing equation 3.14 into equation 3.13, applying Laplace transform with zero initial condition yields:

$$CSP(S) = \frac{K_c\,\theta(S) - P(S)}{R_2} \tag{3.15}$$

Rearranging the equation 3.15 produce a transfer function

$$\frac{P(S)}{\theta(S)} = \frac{K_C/R_2}{CS + 1/R_2} \tag{3.16}$$

Equation 3.16 is the transfer function of the second block, relating the pressure of vessel to the angular rotation of servo motor.

Combining Two Blocks

The two transfer function blocks arranged in series can be combined by multiplying both to produce single equivalent block representing the overall functionality of the system, as shown in Figure 3.4 below.

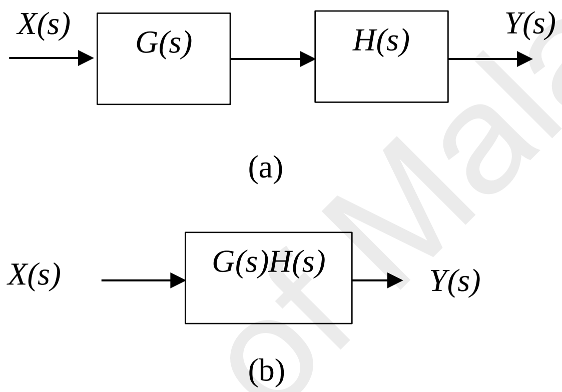

Figure 3.4: (a) Two block in series; (b) Single block equivalent to (a)

Where:

$$G(s) = \frac{K_a/R}{JS^2 + \frac{BR + K_aK_b}{R}S} \qquad and \qquad H(s) = \frac{K_C/R_2}{CS + 1/R_2}$$

Substituting G(s) and H(s) into the block and multiplying them produces the following:

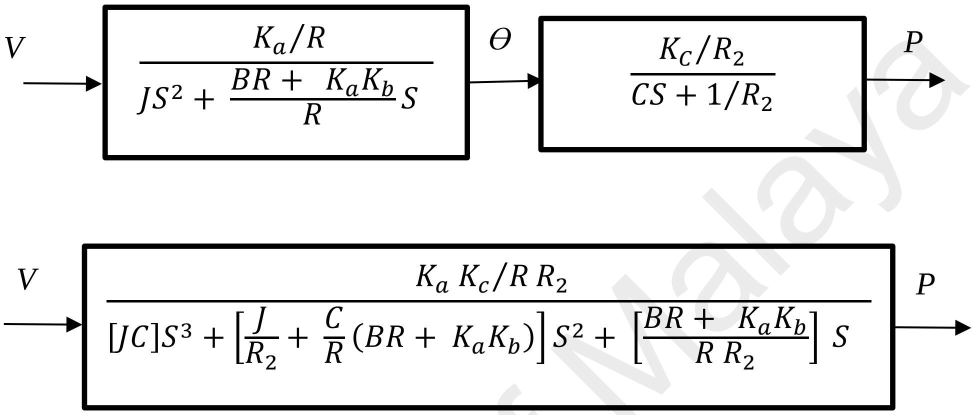

Figure 3.5: Transfer function of the system

This constitutes an open loop system for the system. The next section will discuss in detail about the stability of the system as well variable methods in improving overall controllability of the system.

3.4 Analysis of System Using State Space Modelling

Parameters used for developing the systems are tabulated in Table 3.1.

Table 3.1: Parameter value of the system

Parameter	Value	Unit
J	0.04	$Kg.m^2$
B	0.002	$Nm.Srad^{-1}$
K_a	0.06	$Nm.A^{-1}$
K_b	0.16	$V.Srad^{-1}$
R	1.5	ohm
C	2	$Kg.bar^{-1}$
R_2	1.5	$Bar.s.kg^{-1}$
K_c	1	dimensionless

The above parameters were obtained from literature produced by Ahmed (2008) and reference book of Principle of Electric Machine and Power Electronics (Sen, 2014).

Substituting all the values into combined transfer function produces:

$$System\ TF = \frac{0.027}{0.08S^3 + 0.043S^2 + 0.056S} \tag{3.17}$$

The above is a classical approach towards analysis and design of any control system. Modern technique or also known as state-space approach were used throughout this chapter to design and analysis various control methods.

MATLAB R2013b software were used to develop various modern control design, as well as evaluating the performance of the control method and behavior of the system when it is subjected to an external disturbances. The corresponding state space schematic representation is shown in Figure 3.6 below:

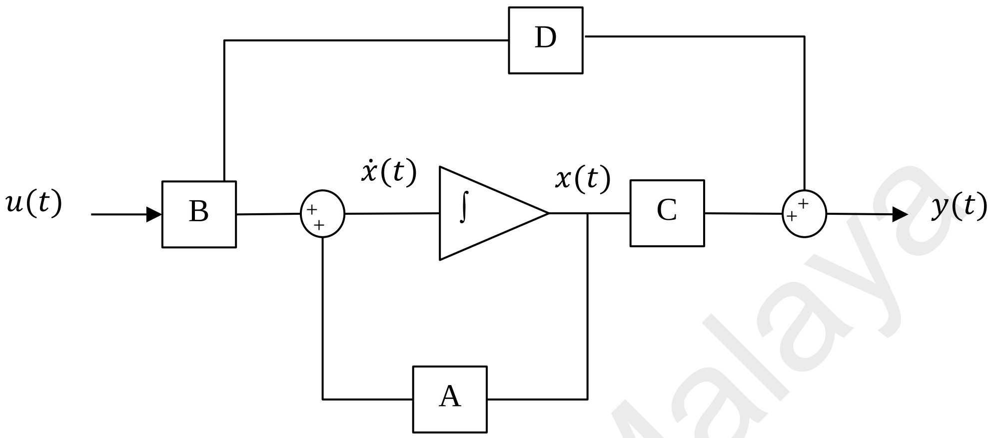

Figure 3.6 : Schematic representation of state space model

The following MATLAB syntax are used to transform transfer function to a state space form of $\dot{x} = Ax + Bu$ and $y = Cx + Du$;

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)
```

Which produces the following matrix A, B, C and D.

$$A = \begin{bmatrix} -0.5375 & -0.07 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0.3375 \end{bmatrix} \qquad D = \begin{bmatrix} 0 \end{bmatrix}$$

Where x is the vector state, u is the vector input and y is the vector output. The above is then translated into MATLAB software to ascertain the stability of the system. MATLAB syntax shown above is written in command editor. Subsequently, state space schematic as shown in Figure 3.7 is developed in Simulink window.

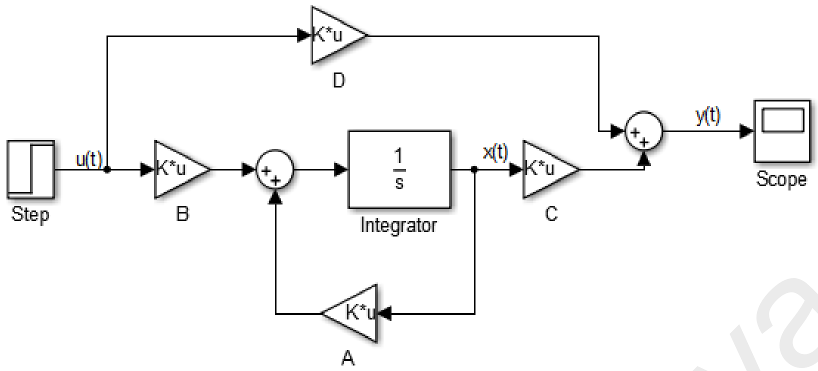

Figure 3.7: State space schematic diagram in MATLAB Simulink

The system behavior is then checked by observing the system output when unit step change is applied to the input. This is known as open loop system. The system is said to be unstable if its output is deviating away, unable to track the reference input. If it is proven to be unstable, it must be then checked whether or not is it controllable. A controller can only be designed to specifications if the system is controllable.

A system is said to be controllable if it is possible to find some input signal $u(\tau)$ for all $\tau=[t_0,t]$, which will transfer the initial state $x(t_0)$ to any finite state $x(t)$ in finite time from t to t_0. In addition to that, in certain system application, not all state variables are measurable. It may be physically impossible to measure due to inaccessibility, or simply the cost of measuring it is prohibitively high. Hence, observability play a role in this case, where it is defined as a measure of how well internal states of a system can be inferred from knowledge of its external outputs. The following explains the method employed to assess the controllability and observability of the system.

Controllability Assessment

The controllability criteria of any linear time-invariant system with the state space representation matrix of A, B, C and D is dependent on the following matrix:

$$M_c = [B \;\; AB \;\; A^2B \;\; \ldots\ldots \;\; A^{n-1}B] \quad (3.18)$$

The system is said to be controllable if the n x m of the controllability matrix of equation 3.17 has a rank of n. In other word, the rank of matrix M_c shall be equal to the number of linearly independent rows and column. The controllability can be checked with MATLAB syntax as follows:

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)

Cs=ctrb(A,B)
Rank=rank(Cs)
```

The following M_c matrix was obtained from Command Window of MATLAB:

$$M_c = \begin{bmatrix} 1 & -0.5375 & 0.21890 \\ 0 & 1 & -0.5375 \\ 0 & 0 & 1 \end{bmatrix}$$

From the result above, the 3 x 3 matrix has the rank of 3 which is equal to the number of independent row and column. The system is then said to be controllable.

Observability Assessment

The observability criteria of any linear time-invariant system with the state space representation matrix of A, B, C and D is dependent on the following matrix:

$$M_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ . \\ . \\ CA^{n-2} \\ CA^{n-1} \end{bmatrix} \tag{3.19}$$

The system is said to be observable if the n x m of the matrix of equation 3.18 has a rank of n. In other word, the rank of matrix M_o shall be equal to the number of linearly independent rows and column. The observability can checked with MATLAB syntax as follows:

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)

Os=obsv(A,C)
Rank=rank(Os)
```

The following matrix M_o was obtained from Command Window of MATLAB:

$$M_o = \begin{bmatrix} 0 & 0 & 0.3375 \\ 0 & 0.3375 & 0 \\ 0.3375 & 0 & 0 \end{bmatrix}$$

From the result above, the 3 x 3 matrix has the rank of 3 which is equal to the number of independent row and column. The system is then said to be observable. With the above assessment, modern control approach can be employed to stabilize the system. The following section will provide detail methodology of different type of modern control.

3.5 Full State Feedback Controller

Full state feedback, or sometimes known as pole placement method, is an approach applied in control system where the desired location of the closed-loop poles are pre-determined, typically at the stable region i.e. at negative half of the S-plane. The reason for employing feedback control is to improve the system characteristics or transient response such as rise-time, overshoot and settling time. Poles location corresponds directly to the eigenvalues where it determines the decay or growth of the response of the system. Recall that the eigenvalues is given as:

$$|\lambda I - A| = 0 \quad (3.20)$$

Which is also known characteristic polynomial of the matrix A in state space model. A schematic representation of feedback control with gain matrix of K is illustrated in Figure 3.8. The state feedback controller can now be written as:

$$u = -Kx \qquad where\ gain\ matrix\ K = [K_1\ K_2\ K_3 \ldots\ldots K_n] \quad (3.21)$$

The new state space representation can now be expressed as:

$$\dot{x} = Ax + B(-Kx) \qquad or \qquad \dot{x} = (A - BK)x \quad (3.22)$$

Recall that stability is dependent upon eigenvalues of matrix A. Similarly, the controller gain i.e. the feedback gain matrix of K can be determined by equating the eigenvalues of $|\lambda I - (A - BK)|$ with the desired poles location such that:

$$|\lambda I - (A - BK)| = (\lambda - p_1)((\lambda - p_2) \ldots ((\lambda - p_n) \tag{3.23}$$

Where $p_1, p_2 .. p_n$ are the desired pole location, carefully chosen so as not to amplify the noise.

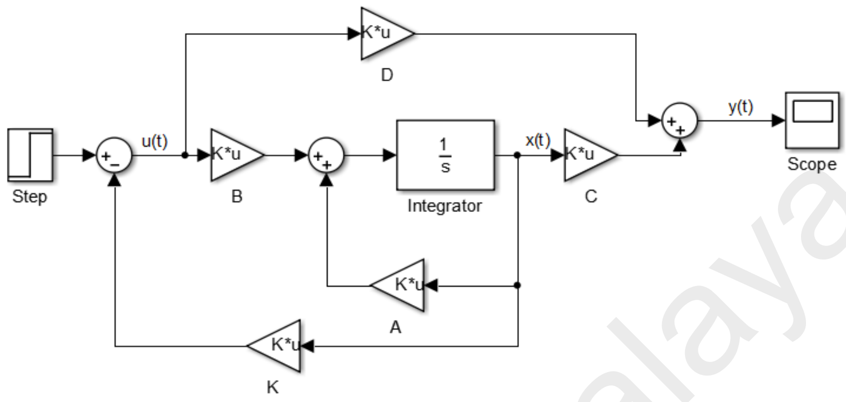

Figure 3.8: Feedback control with $u = -Kx$

The design approach begin with determining the desired pole location. To properly analyse the effect of placing the poles at different location, a set of poles tabulated in Table 3.1 were chosen, and their respective gain matrix of K were obtained via MATLAB Simulink software. The following syntax were used to obtain value of controller gain, K.

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)

CP=[-0.5 -0.7 -0.9];
K = place(A,B,CP)
```

Table 3.2: Set of poles at different location

Set No.	Pole 1	Pole 2	Pole 3
1.	-0.2	-0.3	-0.4
2.	-0.4	-0.45	-0.49
3.	-0.5	-0.7	-0.9

4.	-1	-1.1	-1.2

The value of CP written in the syntax were then substituted with set of poles at different location as in Table 3.2. Controller gain matrix, K is then used to analyse the effect. The step was repeated with different set of poles value, and the output was observed, recorded and analysed.

3.6 Full State Feedback with Feedforward Gain Controller

With the introduction of feedback gain controller, the system can be stabilized within specified transient constraint, when step change of input is applied. However, it was observed that the output was not able to completely track a reference signal hence steady state error will always be presence. Improvement can be made by designing forward gain matrix input to eliminate steady state error.

In steady state condition, state equation is equated to zero as the output reaches equilibrium i.e. completely the same value as reference signal. Therefore, state equation can be represented as:

$$\dot{x} = Ax_{ss} + Bu_{ss} = O \quad and \quad y_{ss} = Cx_{ss} + Ds_{ss} \tag{3.24}$$

In a steady state condition, output is the same as reference input. Let R_{ss} be input to the system, output can be rewritten as:

$$y_{ss} = R_{ss} \tag{3.25}$$

If we let $x = N_x R_{ss}$ and $u = N_u R_{ss}$, then:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} 0 \\ I \end{bmatrix} \quad or \quad \begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{3.26}$$

The control law is given by:

$$u = -Kx + Nr \quad where \quad N = N_u + KN_x \tag{3.27}$$

The design approach begin with finding feedback gain matrix, K by pole placement method and subsequently use the value to work out the feedforward gain matrix N. For this, pole location of -0.2, -0.3 and -0.4 were chosen as it is known to produce huge steady state error when change of reference input is applied. The following MATLAB syntax were used to obtain value of matrix K and matrix N respectively.

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)

Matrix=[A(1,1) A(1,2) A(1,3) B(1,1);A(2,1) A(2,2)
A(2,3) B(2,1);A(3,1) A(3,2) A(3,3) B(3,1);C(1,1)
C(1,2) C(1,3) D(1,1)]
MatrixInverse=inv(Matrix)
NxNu=MatrixInverse*[0;0;0;1]
Nx=[NxNu(1,1);NxNu(2,1);NxNu(3,1)]
Nu=[NxNu(4,1)]
N=Nu+K*Nx
```

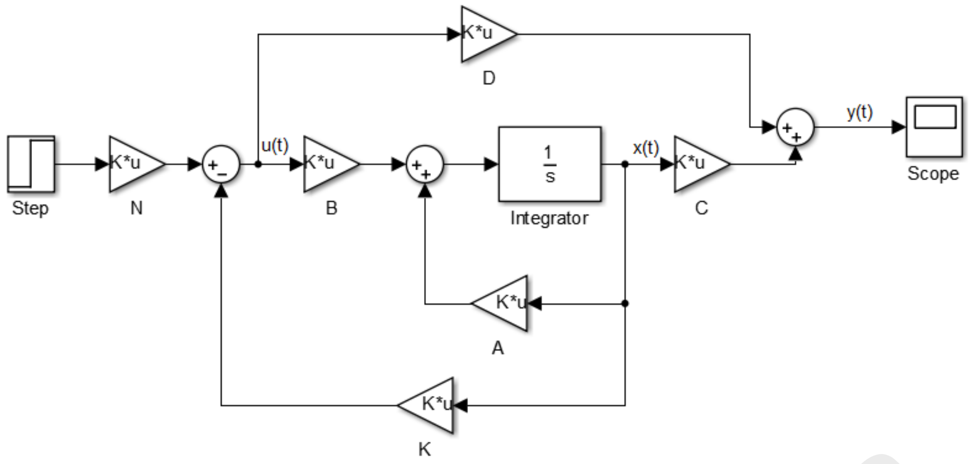

Figure 3.9: State feedback with feedforward gain controller

The following are values obtained from the MATLAB Command Window:

$$N_u = [0] \qquad K = [0.3625 \quad 0.19 \quad 0.024] \qquad N_x = \begin{bmatrix} 0 \\ 0 \\ 2.963 \end{bmatrix}$$

The value of N was then obtained using formula of $N_u + KN_x$

3.7 Integral Control with State Feedback Controller

Introduction of feedforward gain matrix resolves the issue of the presence of steady state error. It works well when the reference input has a step wise change. Typically, step wise change is initiated by a human, i.e. plant operator to suit the change in plant operating throughput. However, this controller design is susceptible to the change of parameters within the system, such that internal disturbance will cause output to deviate from its reference input. One way to eliminate this is by introducing integral controller in the forward path of the system, as depicted in Figure 3.10.

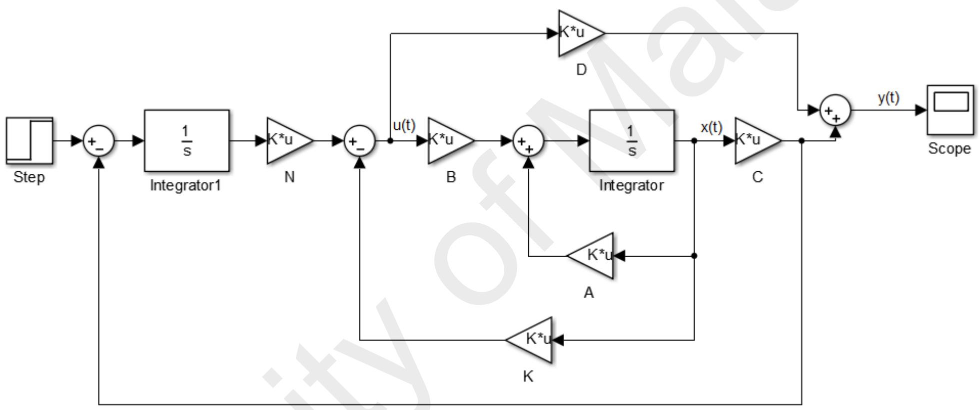

Figure 3.10: Integral Controller

The integral state feedback controller is of the form:

$$u = = -Kx = Nv \qquad \dot{v} = -Cx - Du + r \qquad \dot{v} = (r - y)$$

The closed-loop equation involving the complete set of states are given by:

$$\begin{bmatrix} \dot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} (A - BK) & BN \\ -C & 0 \end{bmatrix} \begin{bmatrix} x \\ v \end{bmatrix} + \begin{bmatrix} B \\ -D \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \mathrm{r} \tag{3.28}$$

The tracking error dynamics will be governed by the eigenvalues of the matrix A' which is matrix $\begin{bmatrix}(A-BK) & BN \\ -C & 0\end{bmatrix}$. By selecting the appropriate eigenvalues for the closed-loop system, the pole-placement method can be used to determine the gains. The following MATLAB syntax were used to obtain the gain matrix K and N respectively.

```
MtrxA_itgrl=[A(1,1) A(1,2) A(1,3) 0;A(2,1) A(2,2) A(2,3)
0;A(3,1) A(3,2) A(3,3) 0;-C(1,1) -C(1,2) -C(1,3) 0];
MtrxB_itgrl=[B(1,1);B(2,1);B(3,1);0];
PoleIntgrl= [-0.5 -0.7 -1 -2]
K=acker(MtrxA_itgrl,MtrxB_itgrl,PoleIntgrl)
N=-K(1,4)
K=[K(1,1) K(1,2) K(1,3)]
```

3.8 PID Controller Design

PID controller is the most common controller found in general industrial applications. PID stands for Proportional, Integral and Derivative terms which serve as individual and/or collective controller's corrective actions to track the system output back to its reference input. Typical algorithm of PID controller take the form of the following:

$$y(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt}$$

Where K_p, K_i and K_d denote the coefficient for the proportional, integral and derivative terms respectively. Proportional action responds only to a change in the magnitude of error and is likely to produce steady state error. Integral action is introduced to eliminate the error for as long as the error exists. Derivative action is applying immediate action based on the rate of change of error.

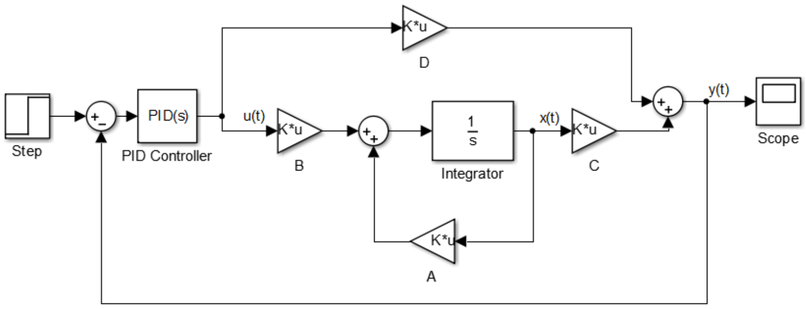

Figure 3.11: PID Controller

Whilst modern controllers employing mathematical manipulation of state space representation to obtain the best possible gain that work best with the system, PID controller has multiple approaches in finding the best possible parameter gain of proportional, integral and derivative. The following are amongst the well-known method in estimating those parameter gain value:

i. Trial and error
ii. Open loop response
iii. Closed loop response with Zeigler Nichols method

Trial and error method

Trial and error method works best for the common system such as liquid level control and fluid flow control. The following describe step by step of arriving at estimated parameter gain of proportional, integral and derivative:

i. Turn off the integral and derivative action
ii. Increase proportional gain until the system output is completely oscillatory
iii. Adjust integral gain until oscillation is completely eliminated
iv. If necessary, adjust the derivate gain to get fast response, improve settling time

However, this method is not recommended for a plant that is under operation as making the output oscillatory will create major disturbance in other part of the systems.

Open loop method

This method is safe to be implemented whilst the plant is in operation. The following briefly describe how it should be done:

i. Put controller in manual, no feedback loop
ii. Initiate a step change of the reference input. Let output stabilizes until it reaches steady state equilibrium.
iii. Obtain dead time, L and rise time, T from the step response graph
iv. Work out parameter gain of proportional, integral and derivative from the table. The well-known table is of Ziegler-Nichols method shown below.

Table 3.3: Ziegler-Nichols method of open loop tuning

Type of Controller	K_p	T_i	T_d
P	T/L	∞	0
PI	0.9 T/L	L / 0.3	0
PID	1.2 T/L	2L	0.5L

However, this method is not suitable for integrating process or system as introducing step change will cause the system to be running away and increase exponentially from the reference input as time approaching infinity.

Closed loop response with Ziegler-Nichols

The system must be stabilized prior to initiating the step. The following briefly describe the steps required to obtain those parameter gain values:

i. Turn off the integral and derivative action
ii. Initiate step change and observe the response. Slowly increase the proportional gain value until output is completely oscillatory
iii. Jot down the proportional gain which cause output to be oscillatory. This is known as ultimate gain, Ku.
iv. Measure the oscillation period, known as ultimate period, Tu.
v. Substitute the value into formula in the Table 3.4: Ziegler Nichols closed loop to obtain Kp, Ki and Kd.

Table 3.4: Ziegler Nichols closed loop formula

Controller	Kp	Ki	Kd
PI	0.22 Ku	0.83 Tu	-
PID	0.3 Ku	1.0/ Tu	0.125 Tu

Closed loop response with Ziegler-Nichols was adopted to be used to obtain the parameter gain value of Kp, Ki and Kd. The values, observation and results were discussed in detail in the next chapter of this research project report.

3.9 Full state observer

The aforementioned state-space controllers are designed employing pole placement method. Such method require measurement of each state variables for use as feedback to the plan inputs. It is important to note that good control requires both the ability to infer what the system is doing (observability), and the ability to change the behaviour of the system (controllability). This has been discussed at length in Section 3.3 to 3.7 of this research project report. As for the physical system developed for this particular research project, the state variables are assumed to be all measurable where sensors can be installed to measure supply voltage to the armature circuit, position of angular rotation of servomotor and pressure at the hydrogen storage vessel.

However, in the instance where one of the state variable is immeasurable due to some physical limitation, a differentiation method can be devised to estimate the state variable. Figure 3.12 illustrates the design of full state observer where $\hat{x}$ and $\hat{y}$ represent the estimated value of the state and output of the system respectively. If the value of unmeasurable state, x is very close to that of estimated state, $\hat{x}$, eventually the difference between these two will converge to zero, such that $x - \hat{x} = 0$.

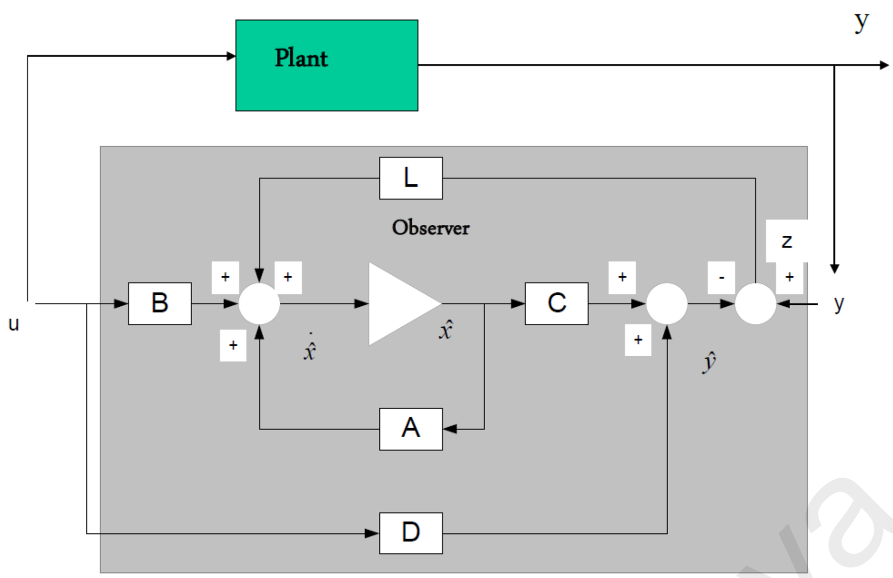

Figure 3.12: Full state observer

The full state observer has the following form:

$$\dot{x} = Ax + Bu + Lz \; ; \; y = Cx + Du \; ; z = y - \hat{y} = Cx - C\hat{x} \tag{3.29}$$

From differentiation method, if both estimated state is equal to the unmeasured state:

$$error, e = x - \hat{x} = 0 \text{ then;}$$

$$\dot{e} = \dot{x} - \dot{\hat{x}} = (Ax + Bu) + (A\hat{x} + Bu + Lz) \tag{3.30}$$

Rearranging equation 3.30 yields:

$$\dot{e} = A(x - \hat{x}) - LC(x - \hat{x}) = (A - LC)(\,(x - \hat{x}) \tag{3.31}$$

Hence, $\dot{e}$ can be rewritten as:

$$\dot{e} = (A - LC)e \tag{3.32}$$

Equation 3.32 indicates the dynamic of the state estimation error. As explained earlier, if the estimated state is very much close to the value of unmeasurable state, and the eigenvalues of $(A - LC)$ lies in the left side of the S-plane, the error will eventually converges to zero as time approaches infinity. If this is observed, the unmeasurable state is said to be of the same value as the estimated state, irrespective of the initial condition of the estimated state.

Given the system is observable, it is always possible to find the feedback gain matrix L, which will give any set of desired eigenvalues for $(A - LC)$. Eigen placement theorem i.e. pole placement method can be used to find the gain matrix L. The characteristic of full state observer is given below:

$$|\lambda I - (A - LC)| = (\lambda + P_1)(\lambda + P_2) + \cdots (\lambda + P_n) \tag{3.33}$$

The full state observer was then constructed in parallel with the system. The following syntax was used in MATLAB and the value of L was obtained from MATLAB Command Window. The response of the output was observed and recorded. This will be discussed in Chapter 4 of this research project report.

```
num = [0.027];
den= [0.08 0.043 0.0056 0];
TF=tf(num,den)
[A,B,C,D]=tf2ss(num,den)

ei=[-3 -4 -5]
L=place(A',C',ei)
```

3.11 Summary

Upon identifying the method and system for sustainable hydrogen production, this chapter is focusing more on the end part of the system chain that is the storage of the hydrogen gas. It is imperative to control the pressure supply to the end user to ensure the plant is running smoothly without interruption. Upon understanding physical system to be controlled, a mathematical model was then developed relating the output to the system input. Upon completion, the open loop test was conducted to access the stability of the system. It was then apparent that the system is not stable hence controller is needed to stabilize the system and take corrective action in the presence of disturbances.

Prior to introducing controller, system was first check for its controllability and observability. A number of modern controller designs were introduced and the design methodology was presented based on their sequence of development, highlighting the advantages as well as the drawback of each and every controller design. Finally, a comparison is made between each modern controller. The observation, analysis and findings are discussed in detail in the following chapter of this research project.

CHAPTER 4: RESULT AND DISCUSSIONS

4.1 Overview

This chapter presents simulation results of employing different type of modern controller to stabilize the hydrogen gas pressure in the vessel. It begins with presenting the response of open loop of the system when step input change is applied, demonstrating the instability of the system which warrants the introduction of controller. The basic full state feedback controller was introduced and the results were observed and recorded. There is a room for improvement where feedforward gain is introduced in addition to the feedback. The inherent limitation of feedback and feedforward controller can be further improved with introduction of integral term at the forward path of the system. A different set of parameters were used to evaluate the differences and the effects they have to the behavior of the output. All these are presented in the following section of this chapter.

4.2 Open loop system response

As the name implies, open loop simply a system where a change of input when applied, produces significant change in output, without output being fed back for comparison with the input. In ideal world, the output is expected to react until it reaches equilibrium upon applying step change of input. In the case of hydrogen storage vessel, a constant pressure of 5 barg is expected to ensure the plant is stable and end-user whom consuming the hydrogen gas is not operationally interrupted.

Input →

$$G(S) = \frac{0.027}{0.08S^3 + 0.043S^2 + 0.056S}$$

→ Output

Figure 4.1: Open loop system

Figure 4.1 illustrates open loop system block with transfer function which relates output to the input. Figure 4.2 shows the system response when step change was applied. It can be seen that the system is unstable where output is increasing exponentially, approaching infinity as time approaches infinity.

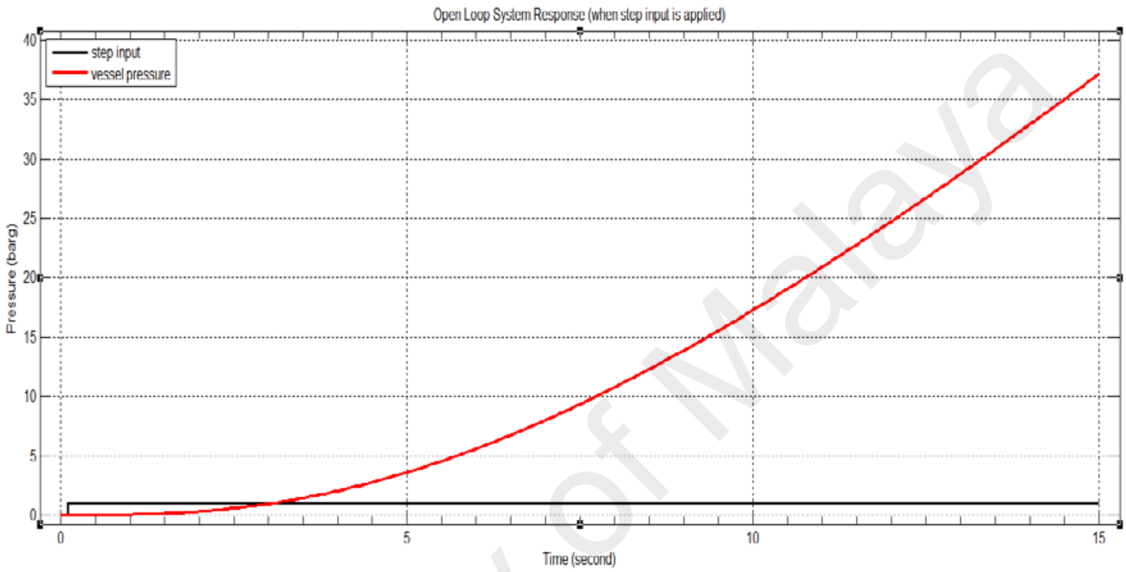

Figure 4.2: Open loop system response when step input is applied

It is evident from the response above that a controller is required to stabilize the plant. However, the controller can only be designed to its specification if it is controllable and observable. Hence, controllability and observability check was carried out with MATLAB tool. The result appears to be positive where both have a rank of 3, indicating that controller can be introduced to resolve the problem.

4.3 Full state feedback controller

State feedback controller was introduced to resolve the problem of instability of the system. The methodology was discussed in detail in Chapter 3 of this research project report. Pole placement method was used to derive the feedback controller gain matrix, K.

To better visualize the effect of selecting poles at different location, a set of poles were chosen and simulated in the Simulink tool.

Table 4.1: Set of pole at different location on S-plane

Set No.	Pole 1	Pole 2	Pole 3	Feedback Gain Matrix, K
1	-0.2	-0.3	-0.4	K_1 = [0.3625 0.19 0.024]
2	-0.4	-0.45	-0.49	K_2 = [0.8025 0.5265 0.0882]
3	-0.5	-0.7	-0.9	K_3 = [1.2625 0.94 0.18]
4	-1	-1.1	-1.2	K_4 = [2.7625 3.55 1.32]

Step input of 5 barg was applied to the input of state feedback controller. The response of each and every set of pole were observed and captured as illustrated in Figure 4.3 below.

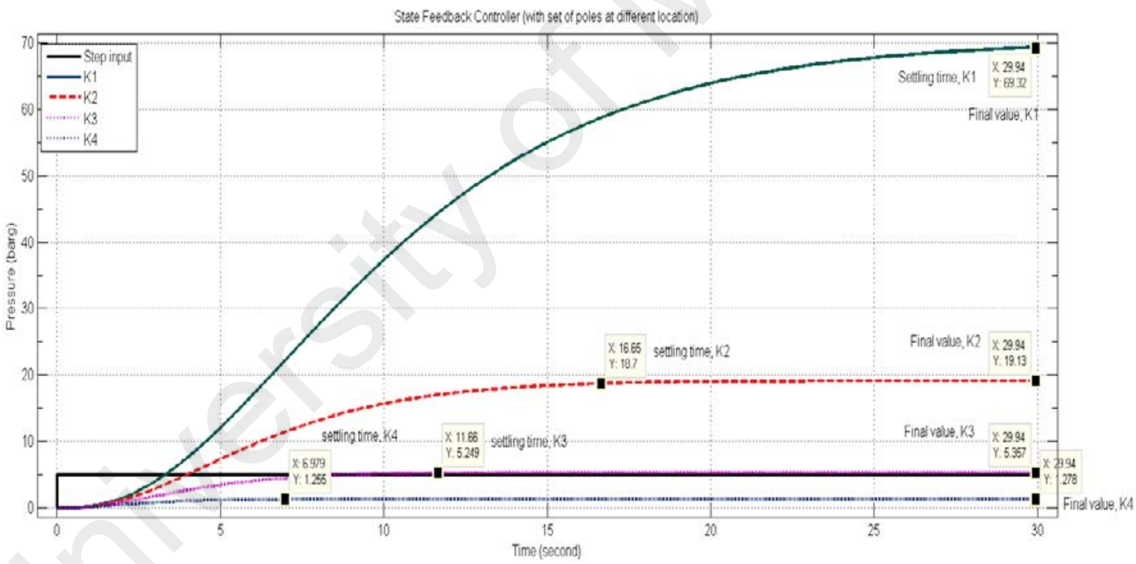

Figure 4.3: Output response of feedback controller at different set of poles location

The simulated data were captured and summarized in Table 4.2. As can be observed from the result, poles which are closer to the location of zero in S-plane produce significant steady state error. Poles location of -0.5, -0.7 and -0.9 appears to be the best location as the final value settles at 5.357 barg, which yields the lowest steady state error amongst all of chosen poles. It can also be observed that as poles are located farther to the left of S-plane, the final value settles below the desired input value.

Table 4.2: Captured data from state feedback simulation

Set No.	Pole 1	Pole 2	Pole 3	Settling Time	Steady state error
1.	-0.2	-0.3	-0.4	30 sec.	+ 64.32 barg
2.	-0.4	-0.45	-0.49	16.65 sec.	+ 14.13 barg
3.	-0.5	-0.7	-0.9	11.66 sec.	+ 0.357 barg
4.	-1	-1.1	-1.2	6.98 sec.	- 3.722 barg

The presence of steady state error make this controller less attractive to be implemented.

4.4 State feedback with feedforward Controller

As explained in Chapter 3 of this research project report, the state feedback controller is capable of stabilizing the system. However, steady state error will always exist such that the controller is not completely able to track the reference input, which is evident in the previous simulation conducted in Section 4.1. This can be improved with introduction of controller gain at forward path of the system. Pole location at -0.4, -0.45 and -0.49 were chosen to demonstrate that the steady state error of +14.13 barg can be completely eliminated by introducing feedforward gain controller, works in combination with state feedback controller.

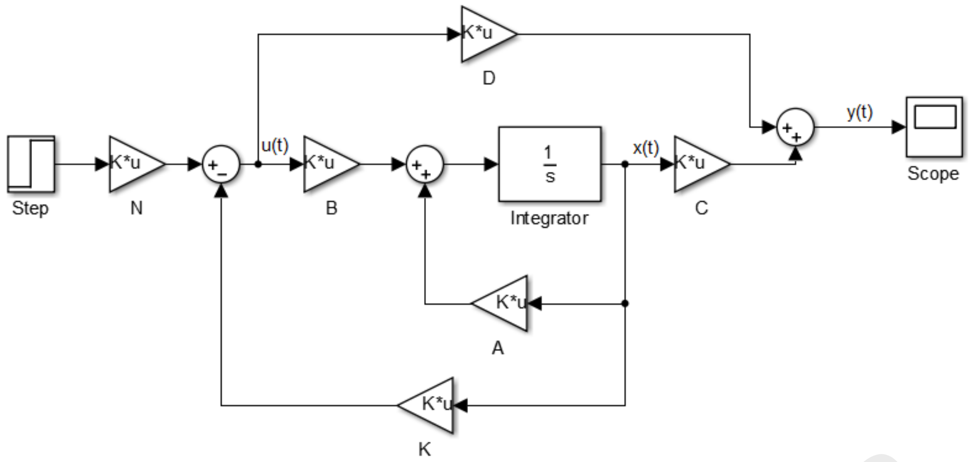

Figure 4.4: State feedback with feedforward controller

It can be clearly seen that the steady state error of +14.13 barg has been completely eliminated whilst maintaining the settling time of approximately 17 seconds. However, despite its ability to completely eliminate the steady state error when a change to reference input is made, it will not work well if the disturbances are presence internally within the system

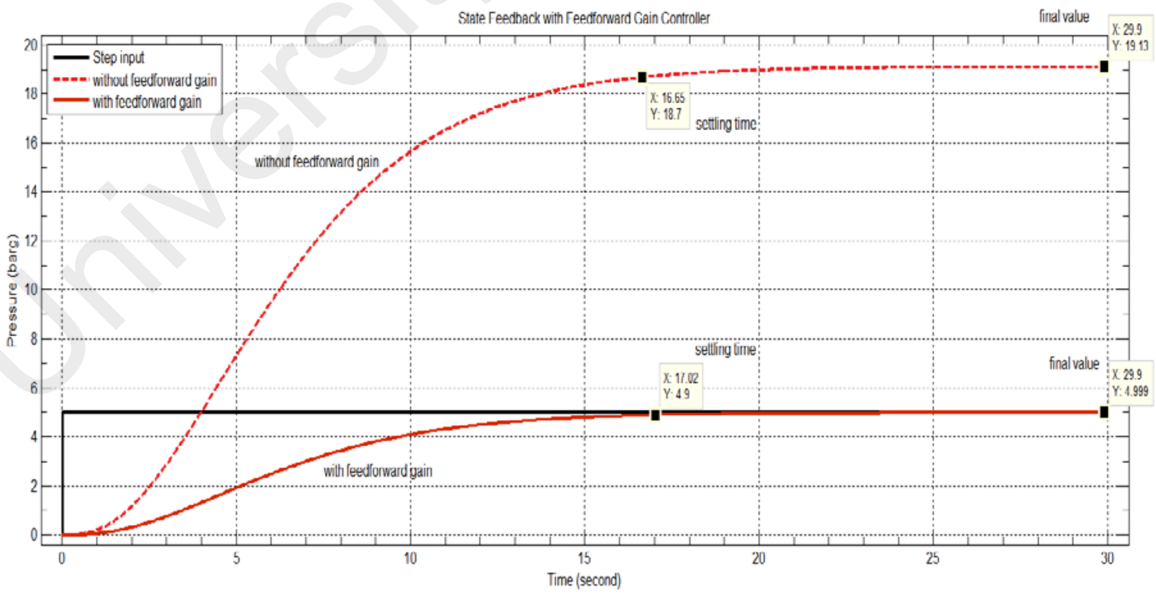

Figure 4.5: State feedback with feedforward gain controller response

This can be demonstrated by adding a source of disturbance in the forward path of the integrator. Figure 4.6 shows the introduction of step input of 0.2 to simulate disturbance within the system.

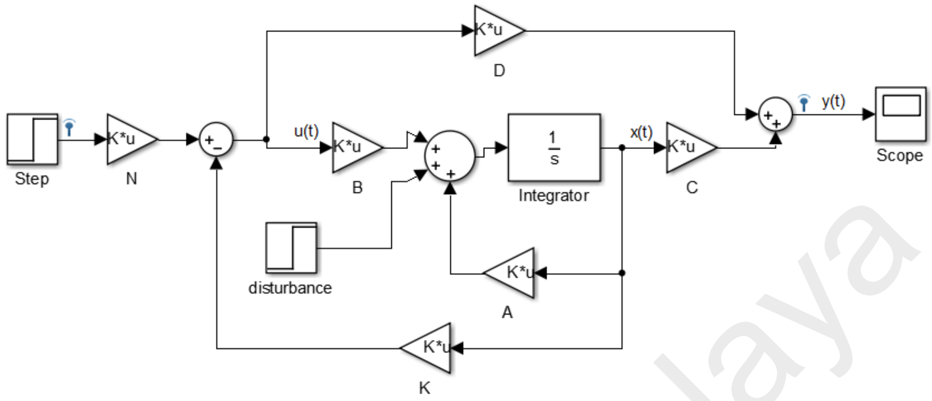

Figure 4.6: Simulated disturbance in the form of step input

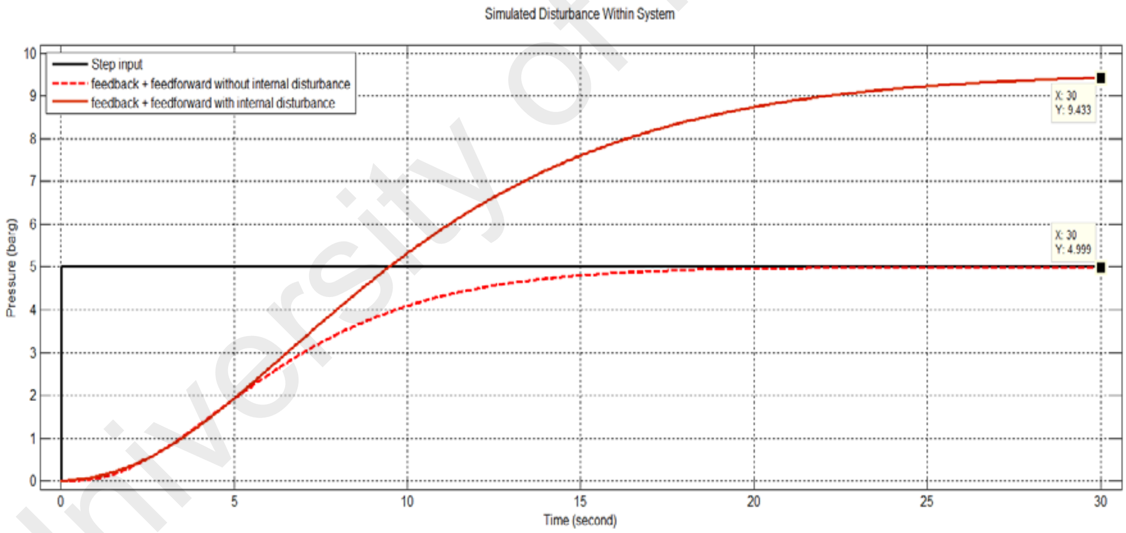

Figure 4.7: Steady state error due to disturbance within system

It can be clearly seen that whilst feedback gain in combination with feedforward gain controller work well when there is a step change in reference input, the limitation still exist when disturbances presence internally within the system. As suggested in Chapter 3 of this report, integral controller can be introduced to overcome this weaknesses.

4.5 Integral control with state feedback controller

With introduction of integral control at forward path of the system, the system is proven to be more robust in addition to improvement in settling time. Figure 4.8 shows integral controller being added to forward path of the previous feedback + feedforward controller, with simulated disturbance presence within the system.

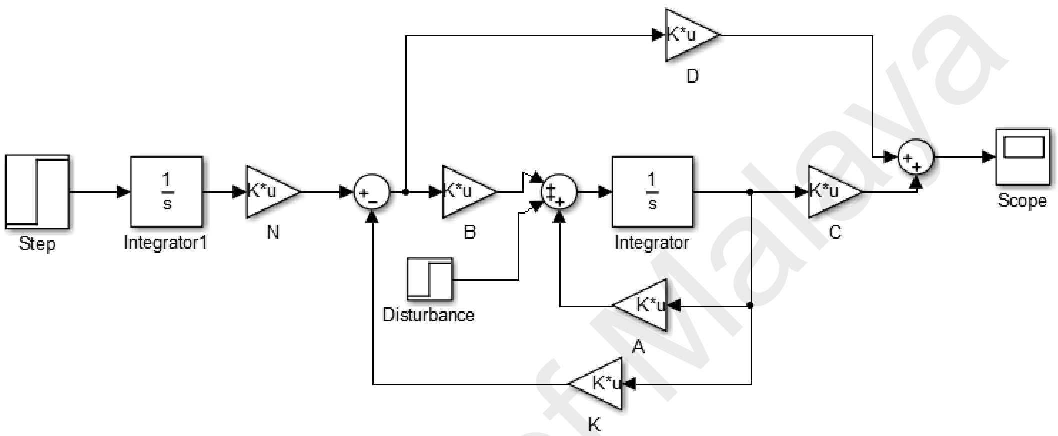

Figure 4.8: Integral controller at forward path

As can be seen in Figure 4.9, despite the continuous presence of disturbance demonstrated earlier in the system, integral controller is able to track the reference input and eliminate the steady state error completely.

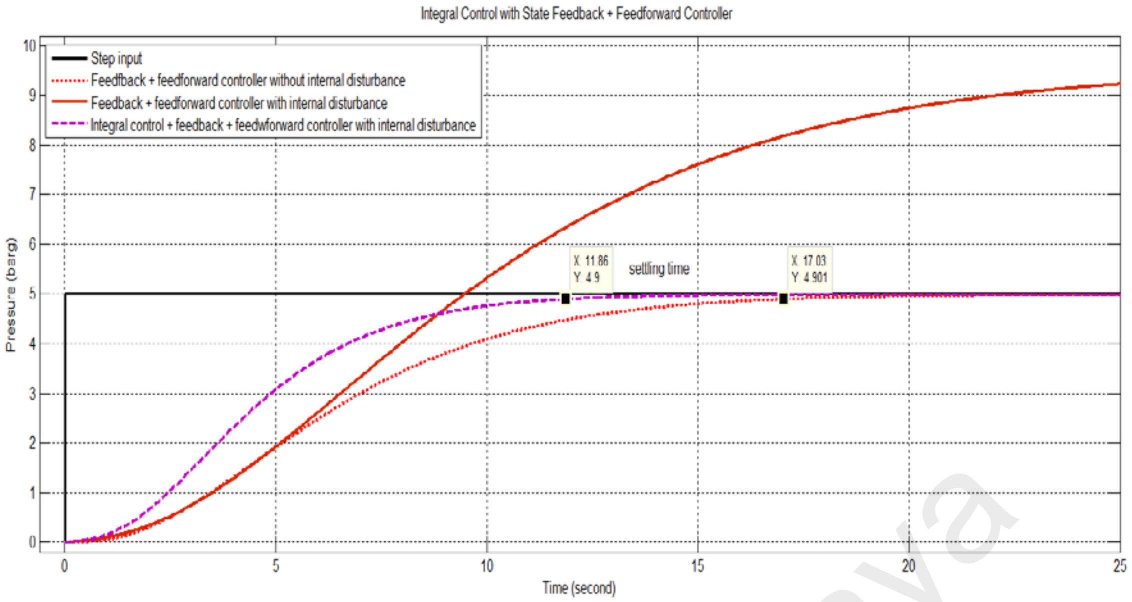

Figure 4.9: Integral controller in the presence of disturbance within system

It can also be seen that the settling time improves by 5 seconds with the introduction of integral controller. It is evident that state feedback controller with integral controller exhibits superior performance that the other type of controllers mentioned earlier.

4.7 PID Controller

As explained in Chapter 3 of this research project report, closed loop response with Ziegler-Nichols method was chosen to obtain parameter value of proportional gain, Kp, integral gain, Ki and derivative gain, Kd. After several trial, the proportional gain which make the output system oscillatory is at Kp = 0.11111. This is also known as ultimate gain.

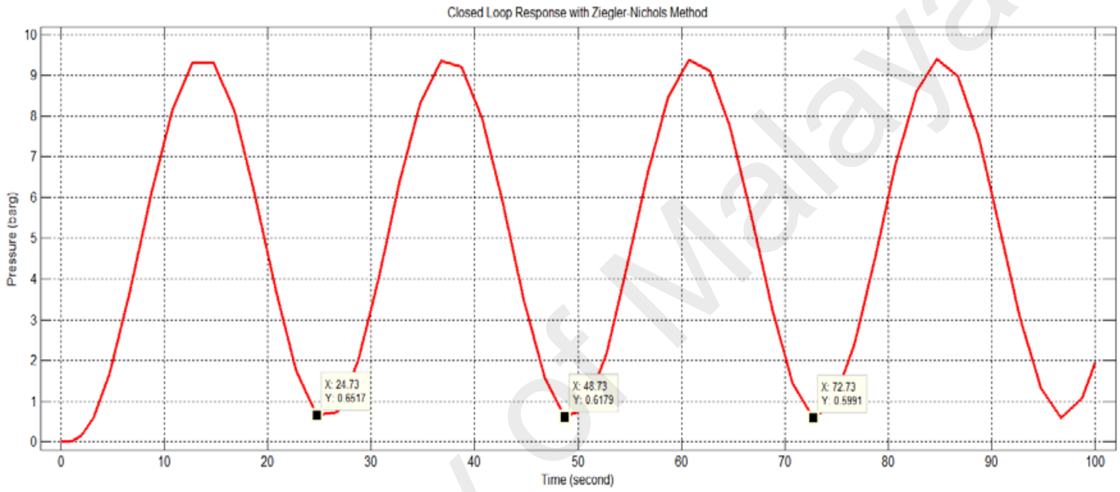

Figure 4.10: Oscillatory system output with ultimate gain of 0.11111

The ultimate period that is the time of one cycle of oscillation is observed to be approximately 24 seconds, as can be seen in Figure 4.10. With these two available information, Ziegler-Nichols formula from Table 3.4 was used to derive the parameter value of Kp, Ki and Kd. The following Table 4.3 summarizes value obtained upon substituting the ultimate gain and ultimate period into the formula. Subsequently, those values are entered into PID controller block, simulated and the response was observed.

Table 4.3: Closed loop Ziegler Nichols calculated gain of PID parameter

Controller	Kp	Ki	Kd
PID	0.033333	0.041666	3

It can be seen in Figure 4.11 that with parameter gain value of Kp, Ki and Kd which were obtained using Ziegler-Nichols method, is able to track the reference input hence stabilizing the system. Note that this is the initial stage in getting the system stabilized. The settling time can be further improved by gradually increasing the Kp and Ki, introduce step change and observing the system response every time changes is made.

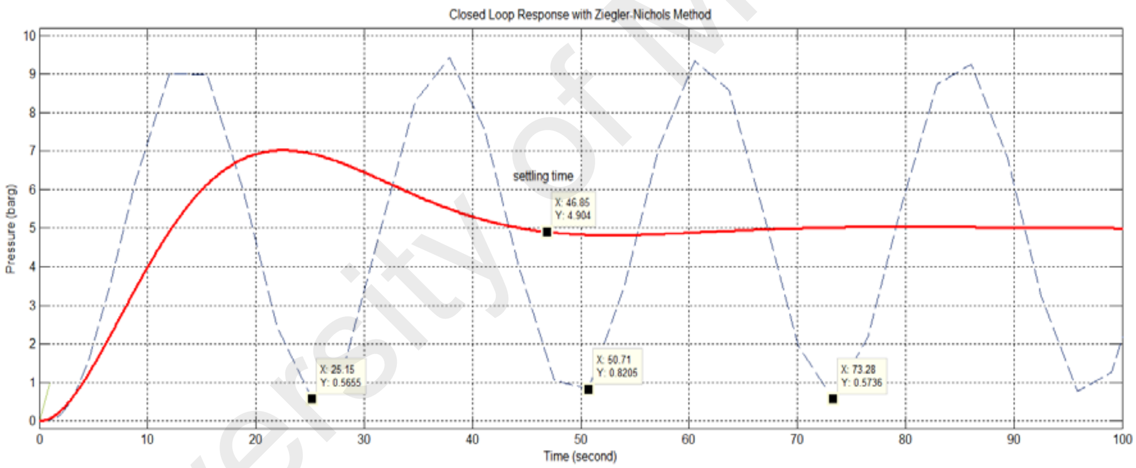

Figure 4.11: Improved response with Ziegler-Nichols method

Figure 4.12 shows improved response and settling time when gain Kp, Ki and Kd were increased to 0.05, 0.17 and 30.2 respectively. Not only it reduces the overshoot, the response time and the time it takes to reach equilibrium are also improved.

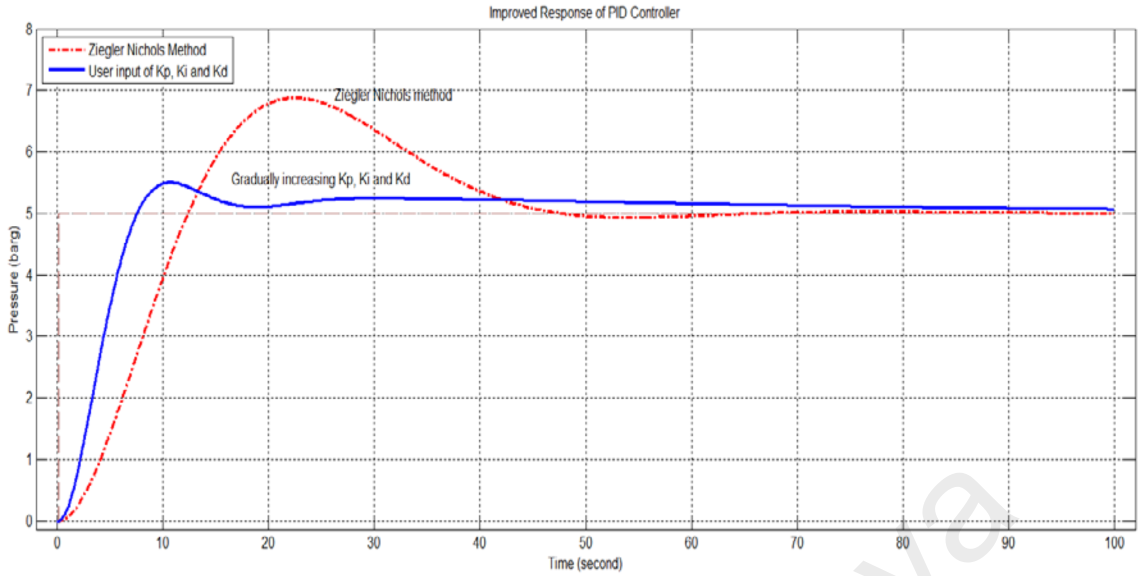

Figure 4.12: Improves response of PID controller

4.8 Full State Observer

As explained in Chapter 3 of this research project report, full state observer can be implemented if one or more state variables are immeasurable. Figure 4.13 shows the implementation of full state observer on the hydrogen storage vessel pressure control system.

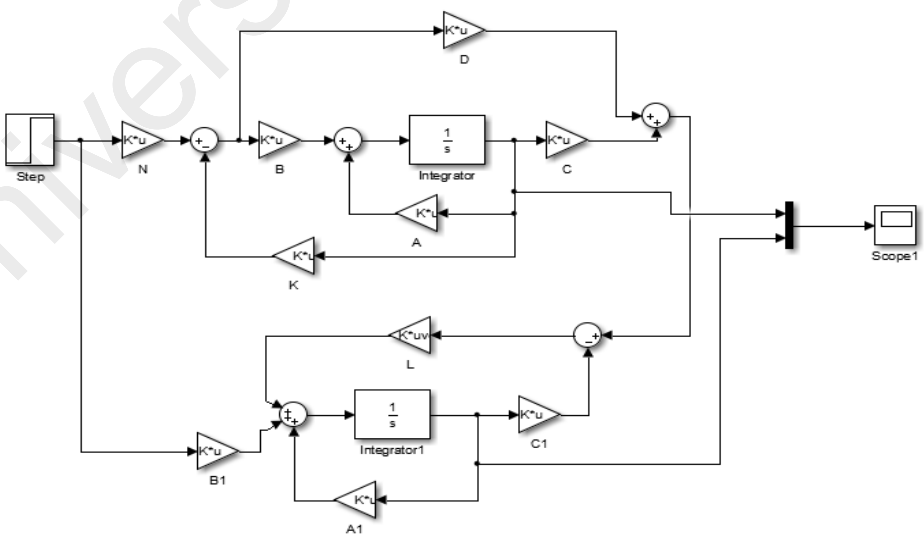

Figure 4.13: System (above) with full state observer (below)

The rule of thumb is to place the poles at least five times farther to the left than the dominant poles of the system (Michigan, 2010). As such, the following poles are chosen:

Table 4.4: Chosen poles to obtain observer gain, L

Pole 1	Pole 2	Pole 3	Observer gain, L
-3	-4	-5	[110.4721 120.7968 33.9630]

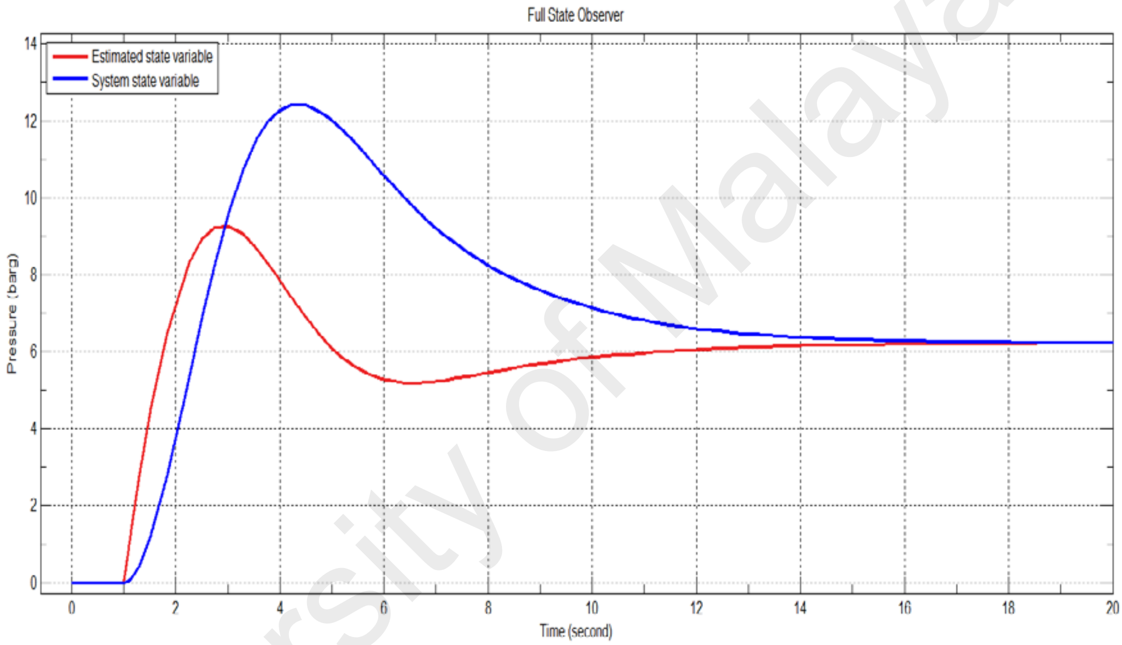

Figure 4.14: comparison between estimated and system state variables

Figure 4.14 illustrates the difference between estimated state variable of the observer with that of the system. It can be clearly seen that as time approaches infinity, both value eventually converges and the difference between them is zero. Full state observer design is particularly useful to be implemented if one or more state are immeasurable.

CHAPTER 5: CONCLUSSION

This research project aims to discuss about the method and system for sustainable and clean hydrogen using water splitting and concentrated sunlight. Concentrated sunlight uses thousands of reflector or mirror to reflect and concentrate sunlight onto a central point to generate heat which in turn used to drive the endothermic reaction of the chemical processes to produce hydrogen. There are quite a number of methods available, however, parabolic through collector (PTC) and solar power tower (SPT) are amongst the technology which are gaining much attention by the researchers and commercial organisations.

PTC make use of parabolic shape reflector which is arranged in combination of series and parallel reflector, where sun is concentrated and directed to the interconnecting pipe with fluid flow through it. SPT comprises thousands of tracking mirrors called heliostat where they reflect and concentrate onto a large heat exchange cylinder mounted on top of the tower. Fluid flows through the cylinder and absorbs heat from the concentrated sunlight and get stored in the thermal storage tank where energy is stored for a later use. This thermal energy can then be used to generate electricity which can then drive the electrolysis process to separate hydrogen and oxygen.

Apart from driving electricity, thermochemical is another viable route in hydrogen production where heat is used as part of endothermic chemical reaction to split water into hydrogen and oxygen. Direct thermolysis requires too high temperature which may not be economically viable, hence the multi-cycle thermochemical is introduced to overcome the technical and commercial issues arising from one cycle thermolysis process. In addition to the above, storage of hydrogen play a key role in the whole operational chain where maintaining the stabile and constant pressure is a key to avoid interruption to the end-user operation.

This can be achieved by introducing valve that regulates the outflow of hydrogen mass flow such that pressure in the vessel will always be kept at constant value. With that thought, a theoretical as well as mathematical model have been developed to control the valve. An open loop test was conducted via MATLAB Simulink to evaluate the system that was proven to be unstable, which warrant the introduction of controller to stabilize the system.

A few modern controllers were introduced namely state feedback, feedforward with state feedback, integral as well conventional P&ID controller. Full state observer, which would be useful in the event state is immeasurable, was also discussed. Each and every controller were evaluated and its performance and limitation was discussed in detail in Chapter 4. In a nutshell, an integral controller with feedforward and state feedback exhibits better performance and the most robust amongst all controllers. Conventional PID controller was also discussed and assessed together. Ziegler Nichols method was employed to tune the controller to a satisfactory performance.

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