



UiT The Arctic University of Norway

Department of Electrical Engineering

Current source Inverter for fuel cell Application

Zainab Hamad

Master Thesis in Electrical Engineering, ELE-3900 July 2023

ACKNOWLEDGMENT

This endeavor would not have been possible without the support from my daughters Astrid, Mariam and Aldana. I am grateful for the patience they have at such a young age, since it was needed the time I have been away from them. I would like to extend my sincere thanks to my husband Ådne Hovde for taking care of our daughters and for pushing me forwards.

I am deeply indebted to my workplace Taco 2030 for giving me the experience and the opportunity to work with full cells. The experience I was given from my workplace is what helped me write this master thesis. As my old teacher told me when I was young, you learn faster when you understand and work with your subject.

The research project on master's degree of science in Electrical Engineering. from the Department of electrical Engineering at the Arctic University of Norway in Narvik

I express my respect and appreciation to Dr. Trond Østrem his understanding and humbleness. He has always been available to help and advise me which have kept me going on. I would also like to give a big thanks to my supervisor PhD candidate Umer Sohail who have guided me this semester.

As Paulo Coelho mentioned in his book *The alchemist*, *the darkest hour of the night comes just before dawn.*

Abstract

In recent years, the scientific renaissance has turned towards alternative energy. Scientific research and dissertations of all degrees, doctoral, Master, and even bachelor's degrees include. Green energy and alternative solution to protect the environment from increasing pollution. Different inverters have been used to increase the potential for power resulting from devices that do not have the efficiency to increase power. Multilevel inverter, voltage inverter, current sources inverter single phase and three phase which-efficiency DC-AC to connected with fuel cell. The inverter topology is present in the project to increase the voltage gain. The MATLAB Simulink results are presented with value for the parameter. The current source inverter single-phase H-bridge topology is used as the source of the explanation (Inverter topology).

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Abbreviation

| | |
|-----------------|---|
| CSI | Current Source Inverter |
| ZSI | Impedance Source Inverter |
| Multi | Multilevel Inverter |
| VSI | Voltage source inverter |
| Fu | Fuel cell |
| PWM | Pulse Width Modulation |
| Ma | Modulation index |
| DC | Alternating Current. |
| AC | Direct Current |
| MOSFET | Metal -Oxide Field Effect Transistor |
| RMS | Root Mean Square |
| MATLAB | MTRixLABoratory |
| IGBT | Insulated Gate Bipolar Transistor |
| CL | Catalyst layer |
| PEM | Proton Exchange Member |
| PEMFC | Proton Exchange Member Fuel |
| $\frac{di}{dt}$ | Change in current with respect to time. |
| $\frac{dv}{dt}$ | Change in voltage with respect to time. |
| PE | Power electronic |
| Pt | Total power |
| WBG | Wide bandgap switches |
| BD | Bidirectional switches |
| THD | Total harmonic distortion |
| SPWM | Sinusoidal pulse width modulation |

Nomenclature

| | |
|-----------|----------------------------------|
| V_{in} | Input Voltage |
| I_{Lr} | Current in the resonant inductor |
| I_{dc} | DC Current |
| C_r | Resonant capacitor |
| R_L | Load resistor |
| D | Diode |
| F | Frequency |
| S1 | Switching MOSFET |
| V_{ref} | Voltage reference |

1. Introduction

1.1 Motivation

Introduction:

The energy used everywhere today is gathered from all over the world. As high up and as far down as we reach and the energy we extract is being used everywhere. At home, on the streets, in public transportation, and elsewhere. Although not everyone is aware of where the energy they consume daily originates from, as of 2021, over 30 billion tons of CO₂ have been emitted globally by oil, gas, and coal [1].

Oil, gas, and coal are typical fossil fuels, sometimes known as nonrenewable fuel sources. This means that this type of energy is depleted quicker than it is restored. Organic materials such as plants and animals are buried under ground after their death and buried in the earth for millions of years and being exposed to high heat and pressure, therefore making fossil fuel a non-renewable fuel source due to the time it takes for its creation [2]. Fossil fuels also account for the majority of the greenhouse gas emissions in the world to date and are a major factor for the global warming phenomenon.

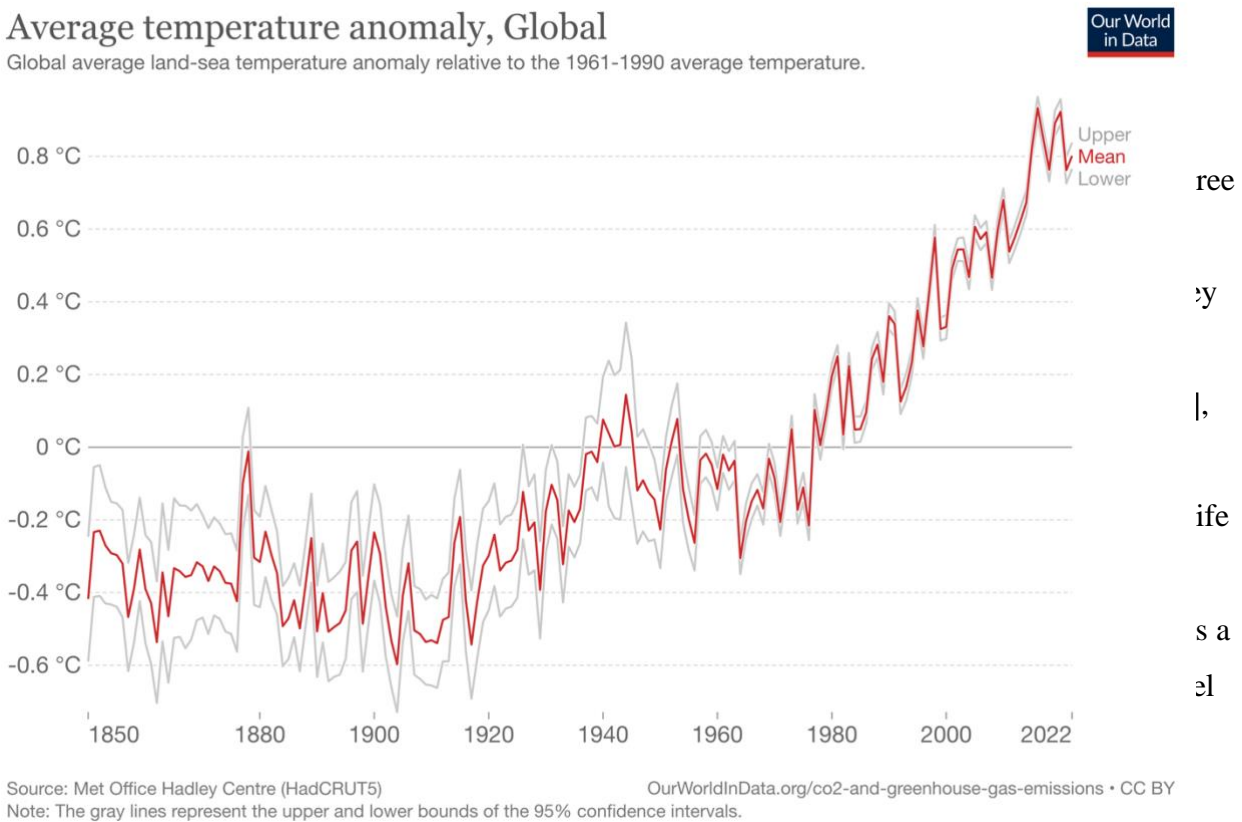
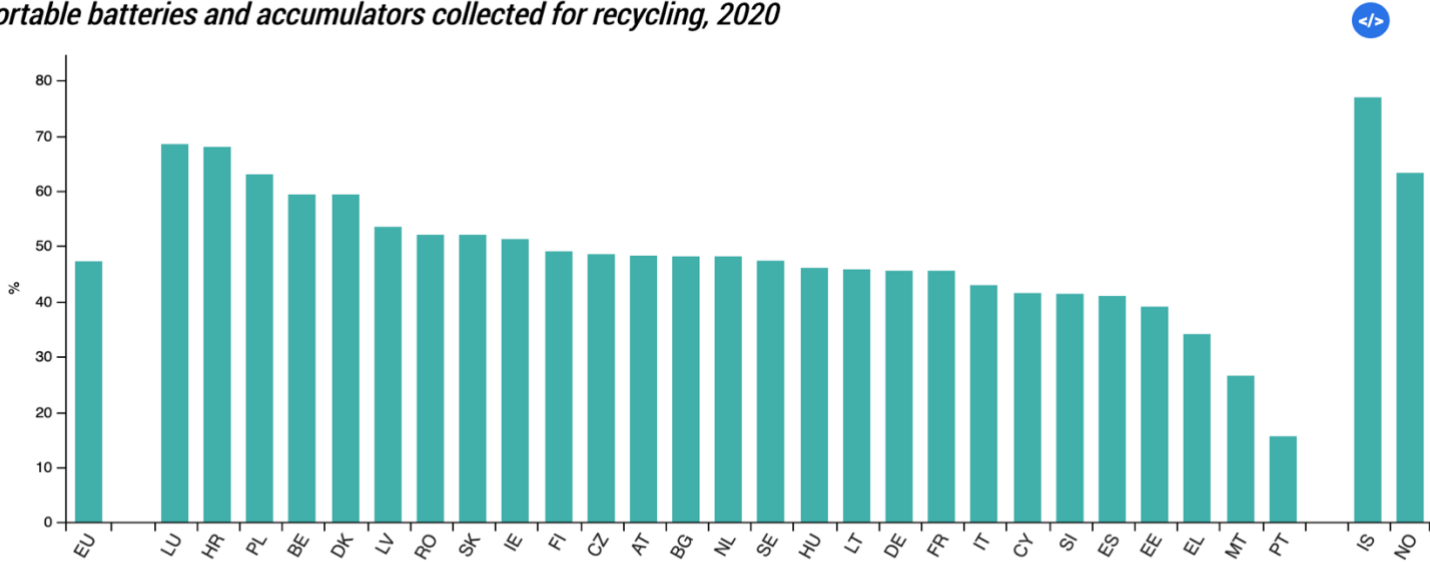


Figure 1 The average world temperature since 1850

A fuel cell can be thought of as a battery, but it is much more than that. Fuel cells and batteries both produce energy through a chemical process, but fuel cells use a hydrogen-based fuel source to generate electricity, however batteries use stored energy to produce electricity [7]. This implies that a fuel cell has a longer lifespan than a battery. Furthermore, depleted batteries must be recycled, which is a fairly simple process, yet not everyone does recycle their batteries, which is very bad for the environment. In 2020 only 47% of batteries and accumulators sold in the EU were collected for recycling [8]. Depleted batteries thrown in the trash end up at landfills which cause the chemicals inside the batteries to leak and pollute groundwater and surface water. This can prove harmful to marine life and can affect us by polluting our tap water [9].

[fig 2]

Portable batteries and accumulators collected for recycling, 2020



Bulgaria: 2019 data instead of 2020
 Source: Eurostat (online data code: env_waspb)



Figure 2 Batteries collected for recycling in the EU by different countries (2020)

Lithium-ion batteries are expensive to produce as well because they need lithium and cobalt which when being mined, pollute the surroundings such as water and air, and take up space which could harbor ecosystems [10], therefore contributing to a more expensive production cost. Fuel cells, however, use hydrogen-rich fuel which is the most abundant element in the universe. Although fuel cells require platinum to work efficiently, which is a rare and expensive material, it does not mean that it would be a more expensive industry because fuel cells do not get depleted, and work more like a generator to power up electronic devices. This

means that fuel cells do not need to be consistently built, but rather enough fuel cells need to be built to have sufficient power output to power entire countries or regions and no more than that.

Car mechanics and experts recommend that you change your car battery about every 3-4 years [11] because a battery degrades over time and loses efficiency over prolonged use. 3-4 years is on average 30 000 to 50 000 miles [12]. STAYERS is a joint cooperation project based in the European union and their goal was to create PEM fuel cell stacks that could have a lifetime of 40 thousand hours (4,5 years) for stationary applications and 5 thousand hours for automotive applications (208 days of continued use) or 150 thousand miles. [13-14]. Which just goes to show how much longer fuel cells could potentially last in the future than our regular batteries today.

As I have shown you, we need to move on and focus on our future. Non-renewable energy sources and renewable energy sources being harmful to ecosystems and us humans; means that we need to evolve with time and take care of the earth as we are supposed to do. We need to focus our energy and resources to the development of fuel cells as this is paramount to our species survival on this planet.

1.2 Project Description

Project Assignment

The fuel cell system, a component of which can assist to enhance the voltage, is the primary task in the project. Although the power coming from the stack is medium, the DC voltage is low, thus the AC link needs to be connected to the common inverter to boost the low voltage input thus increasing the output power. Since the Current source inverter is used for the renewable energy system has some limitations in increasing the output voltage with the single-phase system in different testing. Through the analyses:

- I. The performers for the current source inverter single phase.
- II. The testing with different values parameters pars each parameter.
- III. The value for the output voltage Increase-decreases.

The theory in an application can increase the output voltage on Simulink with Matlab but the real device has a current source inverter single phase DC-AC with a limit value for fuel cell.

1.2.2 Problem Analysis

The interface for the fuel cell system with a single-phase single current source inverter is a challenge. The value of the r parameter with simulation should be changed and testing simulation to measure the maximum upper limit value. The detailed design, description, parameter value and performance analysis. The operation of the current source inverter to

1.2.3 Project Limitation

A selection of excerpts and justifications from the literature study are shown in chapter 2. Clarity and background knowledge will be provided, which will be helpful later when analysing technical facts and comprehending the justification for final judgments. This will also serve as a good foundation for the master thesis' theoretical section. In this project present the current source inverter (CSI) single phase H bridge with analyses for the component, inductor, resistor and capacitor voltage reference.

1.2.4 Project Objectives

- Study CSI performance and fuel cell systems.
- Choosing a suitable CSI topology for with dimensioning of all systems components.
- MATLAB- simulation of CSI based change all parameter value with focus on power electronics output voltage and control.
- Comprehensive analysis of CSI based value for parameter and fuel cell system voltage gain, total harmonic distortion, component count, dynamic response.

1.2.5 Thesis Structure and Layout

The layout and structure of the thesis flow:

1. *Chapter 1: Introduction-Motivation and project description.*

2. *Chapter 2: Literature review present.*
3. *Chapter 3: Fuel cell.*
4. *Chapter 4: The system modeling techniques.*
5. *Chapter 5: The enhanced interactive dynamic of fuel cell.*
6. *Chapter 6: Analysis performance of the system.*
7. *Chapter 7: Discuss and conclude.*
8. *Chapter 8: Scop for future work.*
9. *Chapter 9: References*

1.2.6 Resources (Future)

The simulation for the performance of inverter topology was tested on Matlab/Simulink. For the hardware testing practically in vitro of inverter topology, the type of the following component be required:

- The inverter
- The Fuel cells.
- The voltage sources.
- The indicator
- The MOSFET
- The Diode
- The Resistance
- The capacitor

2 Literature Review of Current sources inverter

2.1 Why current sources inverter

In the modern world with the development of electrical devices and the increase in the market for renewable energy, most of the components with low voltage, and low efficiency are used in energy systems. On the other hand, to avoid the drawbacks of the device and to increase the ability of the electrical power system. The power electronic inverter is a component that has the capability to convert a low value to a high value, they are several types of inverters that should be set up related or independent of the system and the total power needed.

In the industry, electricity is indispensable for the entire world's industry and daily life. It is important that the power is intact and working all the time to ensure all critical point that increases productivity, efficiency, and safety [15] [16]. Electricity is completely dependent on the functioning of both within all industries with the processes involving security and data protection of information technologies. Today reliance on electricity can no longer be replaced by backup generators in the event of a power outage that will take too long to start up, leading to data loss, process errors, and cost [15-19]. Therefore, the current sources inverter single phase DC/AC with high efficiency used on the system. To transfer the DC current of fuel cell converter to AC current.[20]

The current source inverter CSI is an important component to use in the renewable energy system such as wind energy system and solar power energy system [21].

2.1.2 Multilevel inverter

New structures are proposed to be utilized in a phoshybrid multiple inverter for both symmetrical and asymmetrical configurations. Applies to stations with enhanced control of electrical machinery and renewable energy connections. Cost savings and installation space are included. The self-voltage balancing of the capacitor voltage is unaffected by load type, load dynamics, or modulation index. Performance is enhanced, while complexity is minimized.[22]

MLIs give voltage limiting as well as a greater power level. Many good, efficient solutions are provided by using it in high-power applications such as AC motor drives [22-23] and renewable energy integration. gives improved power quality.[22]

Many good, efficient solutions are provided by the MLI topology in three areas. There are different topologies that are employed and give various advantages and performances, but they also rely on several components to work Configuration on figure (3) [23].

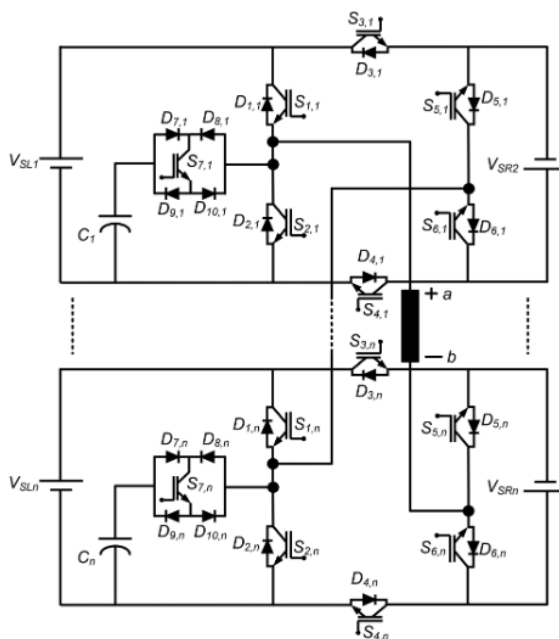


Figure 3 Configuration of the proposed topology [23]

2.1.3 The Impedance Source Inverter ZSI

The Z - Source converter is one of the most intriguing power electronic converters [24]. The challenges of improving performance with a reduction in weight and cost, in addition to high efficiency and development, have been studied during the previous decade. To meet performance requirements, a high level of resolution, adaptability, and improvement has been the emphasis from the outset. Boost factors for inverters have been determined using dominant factors. In addition to determining greater component voltages, input current, and high beginning issues.

Scientists and engineers have obtained speedy information responses to pick converters. With its power electronics (PE), applications [24-25] the Z source inverter (ZSI) has become the most relevant. The basic inverter layout consists of a diode, two capacitors, two inductors, and six semiconductor switches. This ZSI converter has been studied and proven to be a reliable converter in a variety of applications.

Throughout the last decades, researchers have studied the challenges of enhancing its performance with weight reduction and cost, as well as high efficiency and gain.[25]

To reach the performance targets, large quantities of resolution, adjustments, and upgrades have been the theme from the beginning. The dominant factors have been to determine the inverter boost factor as the boots factor of this, inductor/capacitor boots Z - source inverted apologies. In addition to determining greater component voltages, input current, and high beginning issues. Scientists and engineers have obtained speedy information response to pick converters. [24-28].

The Z source inverter (ZSI) has emerged as the most useful for power electronics (PE) applications [24-28]. The primary converter architecture consists of a diode, two capacitors, two inductors, and six semiconductor switches configuration in figure (4) [24]. This ZSI converter has been examined and confirmed to be a dependable converter through numerous types of applications. [24-28]

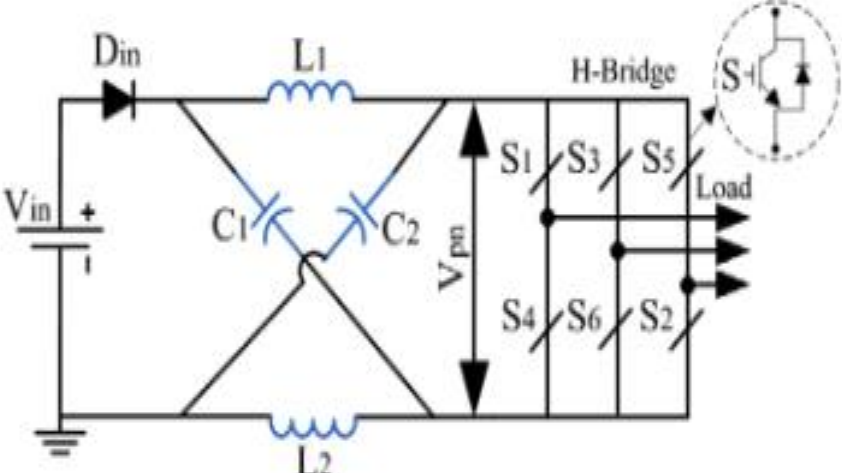


Figure 4 Classical Z-source inverter [24]

2.1.4 The voltage sources inverter VSI

A **voltage source inverter** (VSI) is an inverter that transfers direct voltage current to alternating current from a class of power conversion circuits or renewable energy. To fulfil consumer demands, the utility business requires a clean sinusoidal voltage wave [29]. It is critical to have a solid control approach for a VSI that performs well in both steady-state and transient settings. Many proposed solutions today would be to implement a current control to a multi-loop control strategy to improve the behaviour of the power conversion (VSI). Nonetheless, several additional controls must be implemented [29-31].

Sliding-mode control (SMC) has been offered as an alternative to pulse width modulation (PWM) approaches for DC-AC switching converters with the highest stability and safety in order to produce excellent performance in VSI circuits [29-30] fig (5) [29].

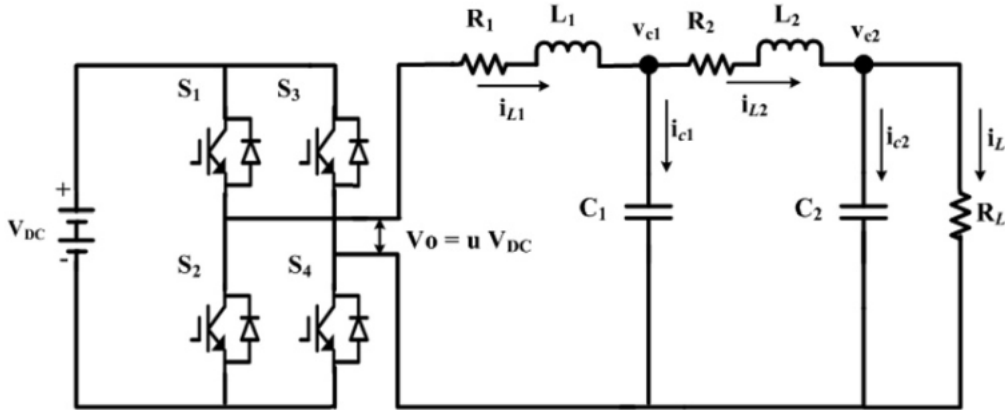


Figure 5 Voltage sources inverter (VSI) [29].

2.1.5 Current source inverter

The voltage source inverter is more popular than the current source inverter because of the vast availability of voltage sources, suitable switches,[32] and its better efficiency, furthermore, the current source inverter does not have as many switches with reverse voltage blocking and a bigger and bulkier energy storage device. The CSI does have an advantage over VSI like some of its more unique features such as inherent boost capability, short-circuit protection, and near-sinusoidal output voltage. [32] fig

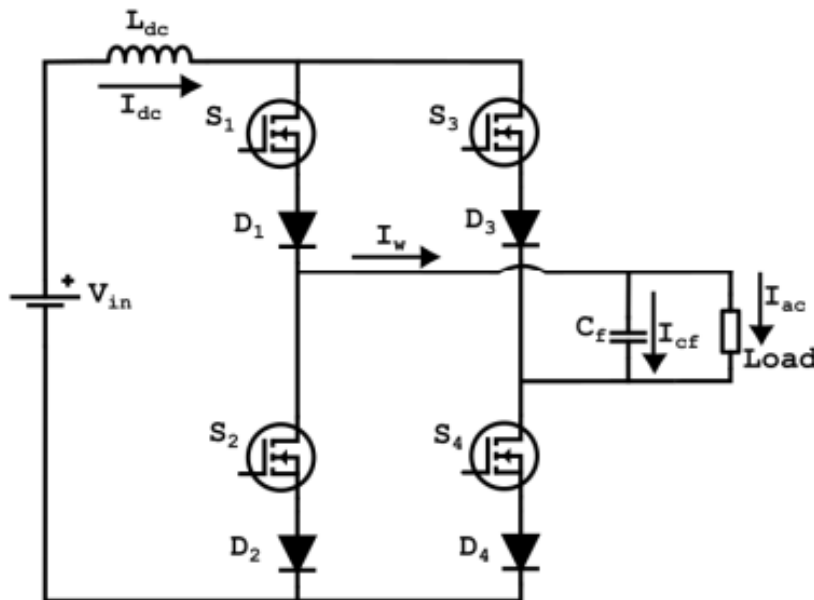


Figure 6 single-phase H-Bridge CSI circuit [32]

Several developments have led to the proposal of solutions for the issues with the CSI. Solutions such as enhancing the RVB capability of semiconductor switches like metal oxide semiconductor field effect transistors (MOSFET) and insulated gate bipolar transistors (IGBT). A series-connected diode is also considered a conventional solution because a series connection of diodes increases the component count, cost, [32] and losses, and it degrades the performance of a CSI. Developments such as a reverse blocking (RB) IGBT reduces losses, however, it could not gain as much popularity within the field because of its poor switching behaviour of its intrinsic diode [32]. Other developments such as bidirectional (BD) switches

which is a series diode is replaced with another anti-series connected active switch [32]. The BD switches that were developed also have RVB capability equal to the forward voltage blocking capability of the active switch, improved dynamic performance, and reduce conduction losses.

A major contributor to CSI's weight, size and efficiency is the DC link inductor which also limits its wide adoption. Despite the negatives of the DC link inductor, [32] it is still considered a more reliable energy storage device than the DC link capacitor of the VSI and especially in high-temperature applications [32]. Wide bandgap (WBG) switches also have the potential to tolerate high temperatures and also lowers conduction losses and has the ability to operate at high switching frequencies [32]. With the use of BD WBG switches, the CSI could significantly improve its performance and reduce the size and weight of the DC link inductor. This means that with the adoption of WBG switches the CSI has the potential of surpassing the VSI in reliability, efficiency, and power density [32].

Unlike CSI, VSI's DC link capacitor acts as an energy storage device, so a high current short circuit can damage the switch. Dead time or blanking time is added to the switching pattern of the switch to avoid short circuits [32]. CSI has an inductor as an energy storage device.

Inductance limits the current in the event of a short circuit. However, for CSI to work reliably, idle states must be avoided. If the inductor current is interrupted, high voltages can be induced by the inductor, destroying the switch [32]. Therefore, an overlap time or anti-dead time should be added to the gate signal of the switch to ensure that an open circuit condition is avoided. Inserting an overlap time ensures the reliable operation of the CSI, however it has an adverse effect on the output current. This increases the total harmonic distortion (THD) and reduces the magnitude of the AC current. [32]

3. Fuel cell

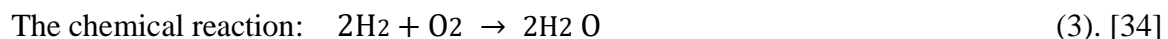
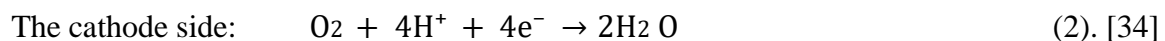
3.1 Electrochemical reaction

Green energy research is currently being undertaken as an alternative strategy to safeguard the environment from pollution and to lower radioactive emission. The best option for this critical issue is to take advantage of fuel cell technology, because the fuel cells has nearly no emissions, ecologically benign, high efficiency, high energy density, and environmentally peaceful.

The PEM full cell is arguably the best technology device to generate energy due to the chemical reaction converter to electrical energy. The chemical operation between the water from the anode side and the hydrogen from the cathode side and electrolyte membrane that use the Proton Exchange Membrane in the fuel cell itself and in same electrochemical operations used to sprat the anode from the cathode. [33]

The most popular theory regarding a fuel cell stack is: Voltage is: 1.23V at 25°C (34) and this is usually the condition, however the low power loss when a proton exchange membrane (PEM) is used inside these cells is influenced by a variety of factors, including materials used in the formation of fuel cells, heat loss due to the internal reaction, and surrounding environment . [34]. fig (7)

The electrolysis processes.



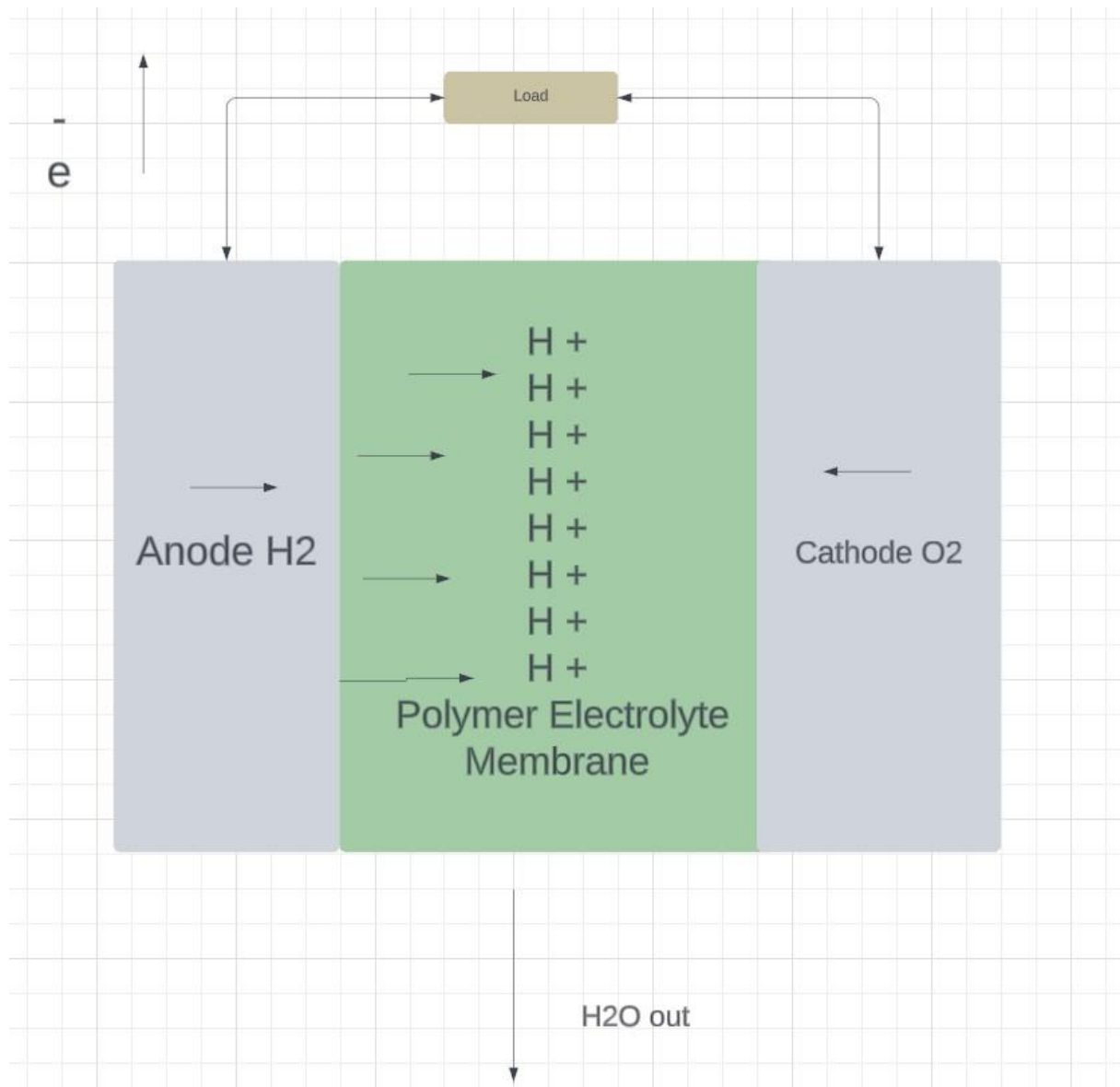


Figure 7 Chemical reaction inside a PEM fuel cell.

The chemical reaction between the two chemical elements oxygen and hydrogen powers the fuel cell, as air enters through the positive side known as (the cathode) a small electric voltage (1V) is produced, on the other hand, hydrogen atoms enter through the negative side that is known as (anode). These interactions inside are known as electronic interactions. Stacks in a fuel cell are connected in series and these stacks produce low voltage, thus an inverter must be used to increase this voltage, however this produced voltage is variable and unstable so, to regulate this variation a DC-AC current source inverter is required in this system. [24][35]

3.1.1 Type of fuel cells

1. Fuel Cell using Polymer Electrolyte:

The electrolyte of this fuel cell has an ion exchange membrane (fluorinated acid polymers, although other comparable polymers can also be utilized). The fuel cell contains water, which produces less corrosion. [35-36]

The water management of the membrane is critical for optimal performance in the fuel cell, so that water does not evaporate faster than it is created, and it must therefore be hydrated.

2. Alkaline Fuel cell Cell:

The electrolyte in the fuel cell is 85% concentrated (KOH). It operates at a high temperature (250° C), as well as at 35-50% by weight (KOH) and a lower temperature (120 C). The electrolyte is held back in the matrix (often asbestos). A variety of electrocatalysts can also be employed (precious metals, metal oxides, spinels, Ni, and Ag). [35-36]

3. Solid Oxide Fuel Cell:

In this fuel cell, the electrolyte is a solid, non-porous metal oxide, often Y₂O₃ - stabilized ZrO₂. Y₂O₃ - ZrO₂ that has been stabilized. The cell runs at temperatures ranging from 650 to 1000 degrees Celsius, when oxygen ions, ironically, take their place. The anode is often Co - ZrO₂, or Ni - ZrO₂, cermet, while the cathode is Sr - doped La MnO₃. When employing concentrated acid, water management in the cell is simple. [35-36]

The process for Exchange

4. Molten Carbonate Fuel Cell:

The fuel cell operates at 600-700 degrees Celsius, with the electrolyte including a combination of carbonates, potassium, and sodium (Na), which is kept in a ceramic matrix of LiAlO₂. High operating temperatures in the anode and cathode promote the connection, making the usage of precious metals unnecessary. [35-36]

5. FEZ CeU phosphoric acid:

The electrolyte in this fuel cell is concentrated phosphoric acid, and it operates at 150 - 220 degrees Celsius. To retain the acid in the matrix, silicon carbide is utilized. At low temperatures, phosphoric acid is a poor ionic conductor, which can cause CO poisoning of the Pt electrocatalyst in the anode. [35-36]

considering that concentrated phosphoric acid is higher in stability than other acids, PAFC is able to operate at the high end of the acid temperature range.

In the anode and cathode PT Molten Carbonate Fuel Ce ZZ, the silicon matrix and electrocatalyst. [35-36]

4. The system modeling techniques.

4.1 current source inverter topology

The system builds of single-phase H-bridge [27]. The Circuit configuration in Fig (8). The Component performance on the DC side, a DC voltage source (V_{in}) is connected in series with an inductor (L) to establish a DC current source.

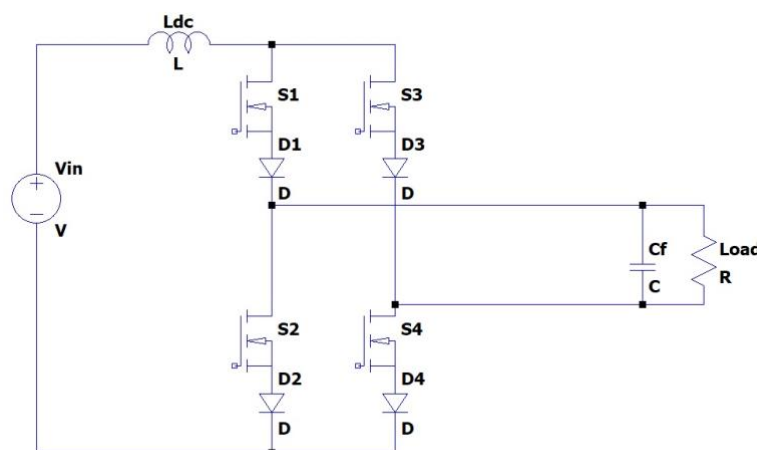


Figure 8 Current sources inverter

The circuit connected the series with the inductor with MOSFET (S1, S2, S3, S4), and a diode is connected with the series for each MOSFET. Throughout the Pulse-width modulation (PWM) signal the CSI converts the DC current. On the AC side the output capacitor filters the PWM signal and the current for C current PWM Iwm, though the Cf as a filter improves, smooth current and voltage direct to load resistance (RL) and is connected purely with a Cf.

With Table for technical analyses value below:

| Parameter used in Simulink | Value for parameter CSI |
|--|----------------------------|
| Input voltage | 40 V |
| Inductor Ldc | 50000μH |
| Switching frequency(fs) Triangular signal | 22 kHz |
| Fundamental frequency | 50Hz |
| Amplitude | 1 |
| Capacitor filter | 100μF |
| Resistance | 20Ω |

The mathematical equation of operation [41] for the circuit inverter blow:

$$L \frac{di_s}{dt} + ri_s = V_s - V_i \quad (4)[40]$$

$$C \frac{dv_o}{dt} = i_o - \frac{V_o}{R_l} \quad (5)[40]$$

Where is r resistor for the inductor. $v_i = dv_o$ and $i_o = di_s$ are the dc voltage input and ac are the output current which is produced by PWM operation [40]

Table 1 Technical analysis value

The system performance for CSI with plus width modulation signal were proved behaviour response. The control system technical building is related to the relationship between the input and the output voltage to increase the voltage gain. The PI controller has several applications to solve the issue for the CSI.

There are several methods advanced for control systems for current sources inverter three phase system in the scientific research papers. The par design should have its own control system to meet the requirement and performance of the system itself. However, for the single-phase system with current courses inverter H- bridge the value for parameter determination to achieve the performance for the system.

4.2 The system behaviour with the control system

4.2.1 The Control system PI Controller design.

The PI controller sitting performance was hard to control. The parameter's value with analysis for the converter and the system itself (single phase system) which required an intelligent-scientific setup adjusting value parameters per each simulation on the other hand, parameter value experiments were set with basic manual tuning testing through the tuning general utilizing requirements for K_p and K_i related to the system performance. The circuit configuration in. Fig (9)

The value for tuning changed with optimizing technical advances for CSI with a fuel cell to aquiline a smooth voltage track output for the DC current. An improvement is shown on Simulink.

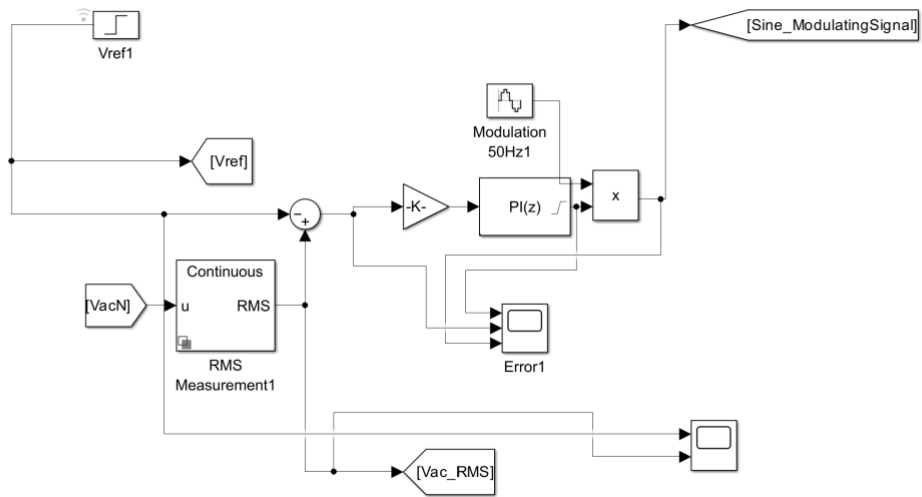
The analysis shows the system for a single phase on the CSI with a closed loop to achieve the output voltage (voltage gain) proportional to V_{ref} .

In Simulink for CSI with the control system is achieved in simulation fig (10). Parameter analysis is performance changed with other parameters. The analyses for system characteristics for CSI independence of the value and the factors, par each parameter has effect for the output voltage to track the output voltage (V_{out}) with minimum ripplon on DC current.

In the simulation start with step response decrease the gain output on time and after a while (1.5s) increase the voltage in order to keep track on the DC current as mentioned. Fig (11)(12).

.

The parameter value on the close system with step response below Tab (2) :



| Parameters | Value |
|---------------|---------------|
| Capacitance | 100 μ F |
| Inductor | 50000 μ H |
| Input voltage | 80V |
| Initial value | 60V |
| Frequency | 22KHz |
| Amplitude | 1 |
| Resistance | 20 Ω |

Figure 9 Closed loop

Table 2 Value for closed loop

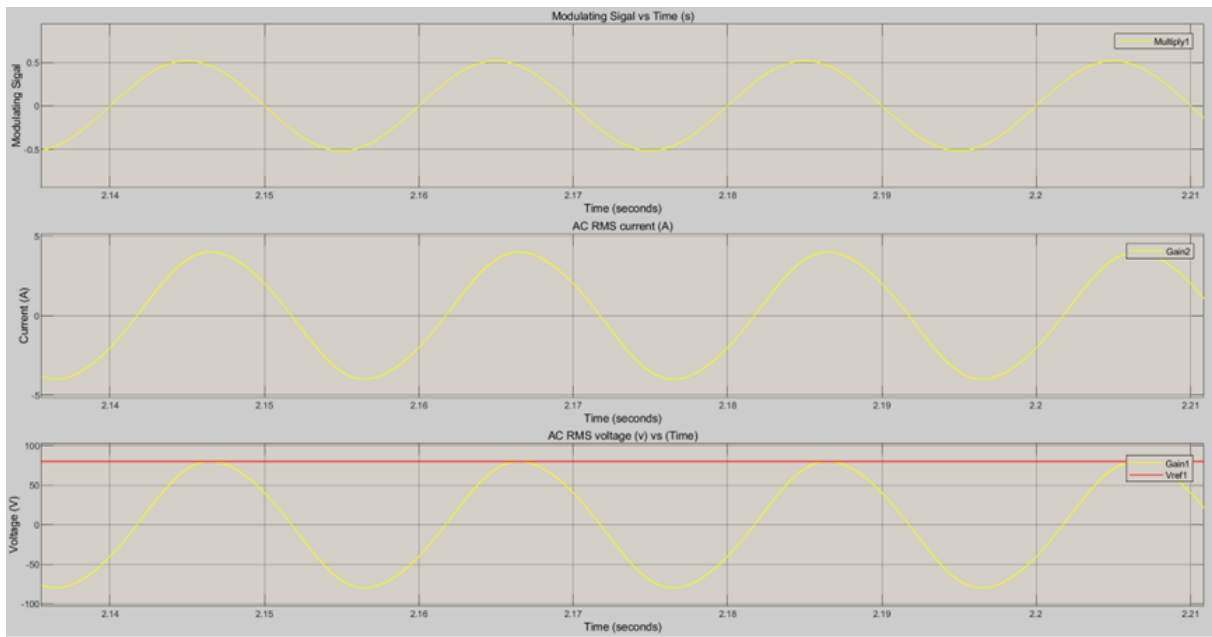


Figure 10 Closed loop system without step response.

The output voltage tracking the DC current after step response.

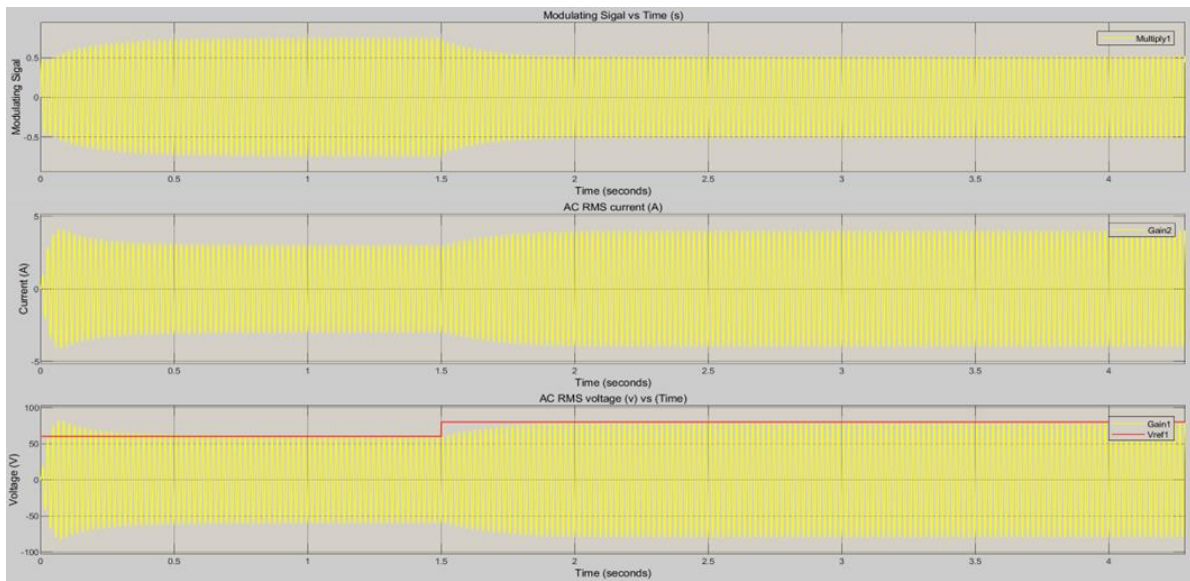


Figure 11 Closed loop system with step response.

Simulation starts with a 1.5s decrease voltage over time and after 1.5s has passed the voltage is increased with the DC current.

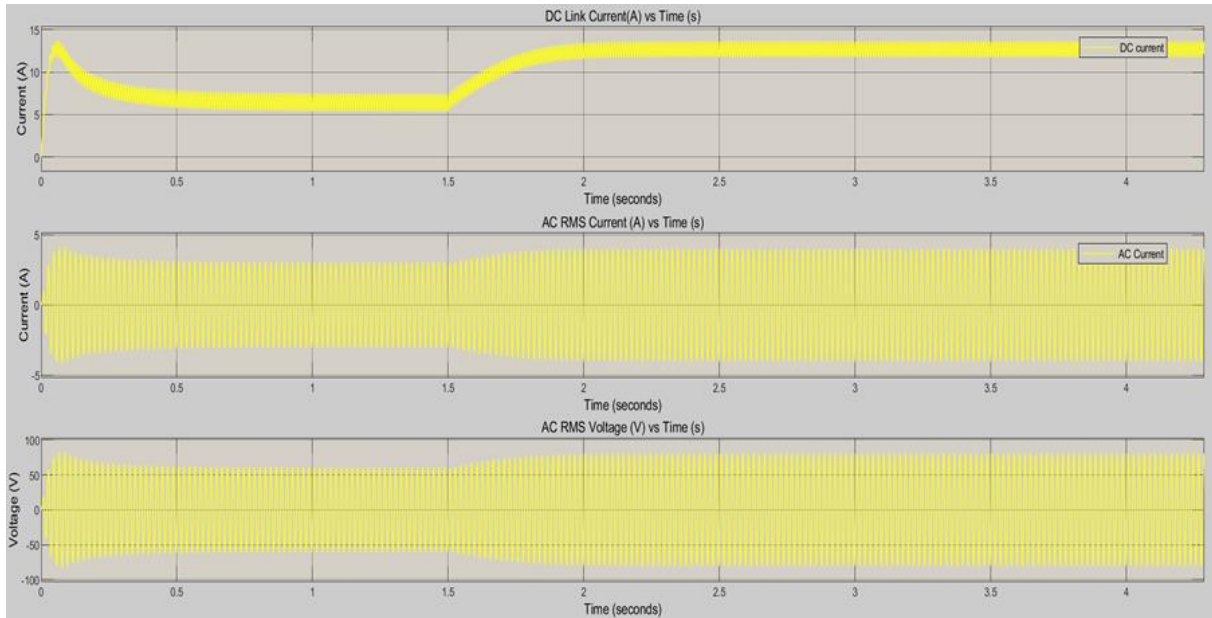


Figure 12 Closed loop system with a step response "the ripple."

Figure (12) shows the step point and the ripple in the DC current.

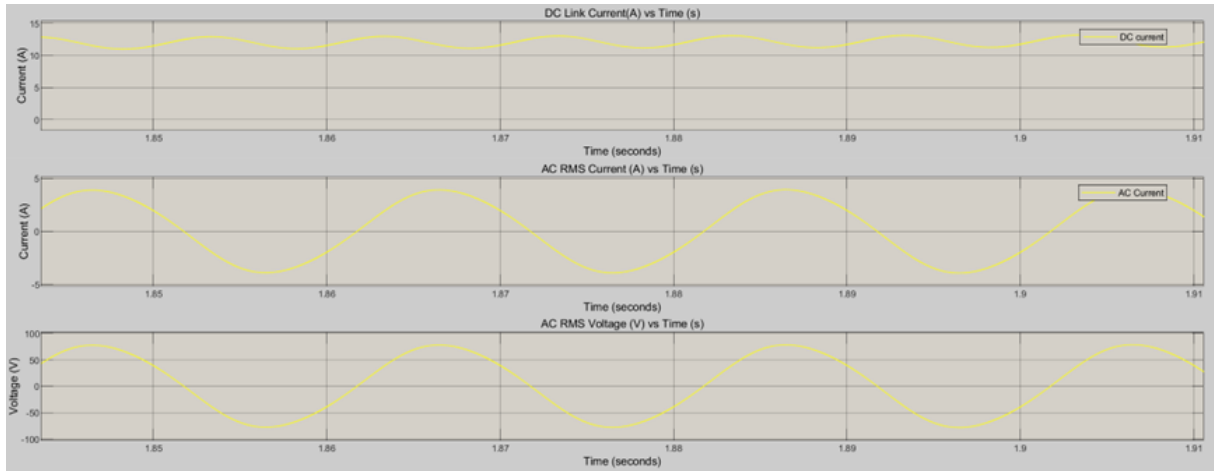


Figure 13 Closed loop system after step response.

This figure (13) shows the ripple decrease after step response.

The question from the system performance with **the value for the V_{ref}** :

The answer will be Chapter 7

1. **What** is the main value that will be the testing result for the output voltage?
2. **What** is the upper limit for the maximum voltage from the value for resistance?
3. **What** is the verified relationship between the modulation index value and the control system?
4. **What** about the resistance in the inductor?

5. The enhanced interactive dynamic of fuel cell

5.1 The fuel cell logic

Today's energy demands development and shifts to a new way of thinking, which is critical for today's energy use. Due to rising power rates, as well as improvements in air quality and capacity, the search for innovative solutions must be increased. Within an achievable technology, there are six varieties of opposing fuel cells PEM. Lard, carbonate fuel cell, phosphoric acid fuel cell, polymer electrolyte membrane fuel cell [41-42], direct methanol, and proton exchange membrane fuel cell are the fuel cell kinds. During a power outage, the output power from a membrane is amplified and delivered to a load using a PEM fuel cell (1.26KV). The technology is visible and appears to be cleaner and more efficient as an alternative to burning gasoline and other fossil fuels. With its fuel flexibility [41], we have portable power. The shift in temperature over time has been a pressing concern throughout this investigation. The research goal was to analyze the production behavior in a model parameterized to offer a characteristic acceptance category of cornucopia fortified the fuel cells that is reinforced with air and hydrogen. In a simulink model [41-42], a test system provides a result of the output behavior over time. A fuel cell has been used in the chemical industry to create electricity with water and heat as byproducts. Their embryonic solicitations are directed at energy structures as huge as a power plant and as little as a laptop computer. Since the discovery of fuel cells in 1840, it has risen via resurrection to

become a contender in the field of alternative energy research. A number of identical cells have been combined to achieve a satisfactory effect [41-42].

5.2 The fuel cell interface with DC- AC converter

The fuel cell stack is a modern technology with a single-phase system. There are many reasserts applications for the fuel cell with three-phase I. On MATLAB Simulink library and example characteristics tree phase CSI are more than a single-phase CSI.

The fuel cell stack components model is available in library with CSI for three-phase CSI and a single phase. The component of the fuel cell stack has the ability of chemical and electrical factors to affect real fuel cells as current, voltage, flow rate for air, oxidant, hydrogen, temperature, efficiency, fuel and air pressure.

The hydrogen fuel cell model on MATLAB Simulink relates to performance behaviour chased the system for CSI with a system for PI controller. The fuel cell stack setting up direct with the source electrical input voltage in the DC line as an electrical logic component.

The Proton Exchange Membrane fuel cell (PEMFC) with a constant function of block parameters from the Simulink formed logic.

5.2.1 The fuel cell interface with DC- AC converter and Pi controller

The main technique of setting components maintenance related to value for parameter components on MATLAB for technical specifications of the Current source inverter and control system for signal phase value. The stack of fuel cell performance work achieved functional with output for CSI and PI controller.

The output voltage and the current of the fuel cell stack tested achieved a smooth DC current track with output voltage. Several measurement framework logics have been tested to comprehend system work with a fuel cell.

The parameter specification value for the fuel cell stack model from the library of MATLAB Simulink (PEMFC) with the value of electric power (energy) is 1.26kW with a Direct current voltage 24Vdc as compared to a component chosen.

Below is the nominal value parameter of the fuel cell in the MATLAB block performed response dynamic value for the whole system visual: Fig (14) and Fig (15).

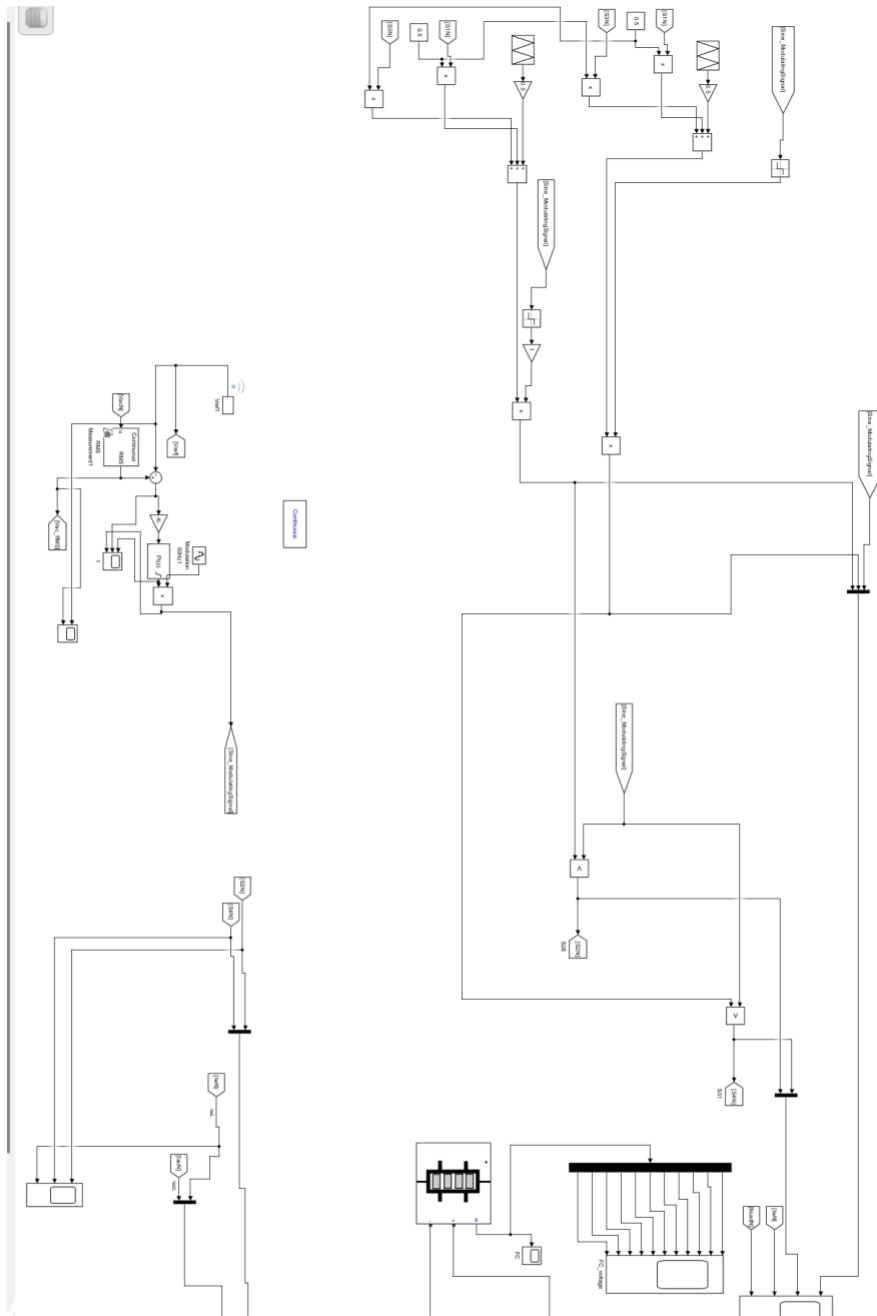


Figure 14 The side of the FC logic and PI controller

The figure shows the system of the fuel cell logic and control system

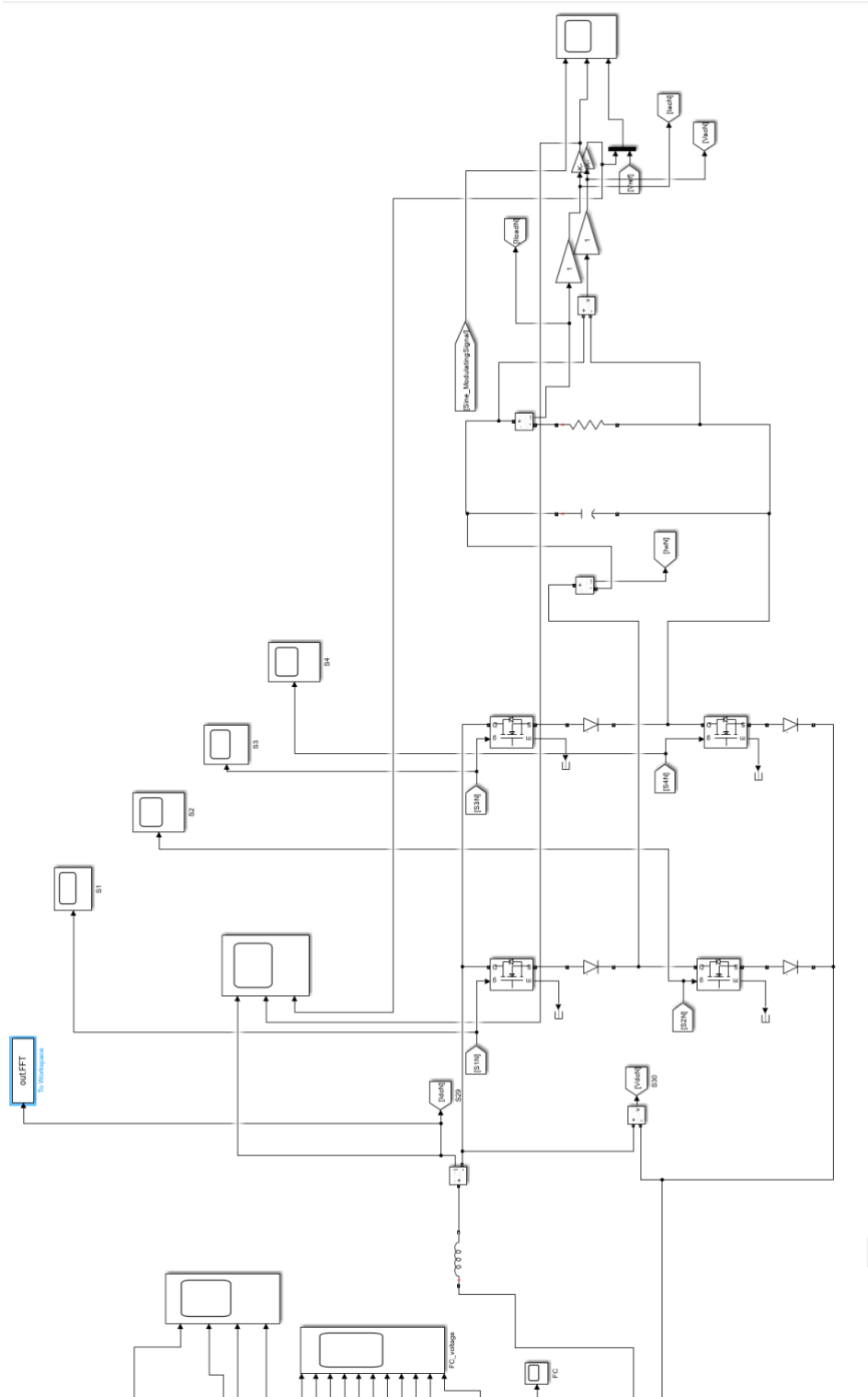


Figure 15 The side of the fuel cell as input

The side from the fuel cell as input, current course inverter and the output with capacitance and the resistances. Parameter value from whole system in the MATLAB simulation below.

| Nominal and electrical parameters | Nominal and electrical value |
|--------------------------------------|------------------------------|
| Nominal (stack powe) | 1259.69 W |
| Maximal (stack power) | 2000 W |
| Resistance (Fuel cell) | 0.61871 Ω |
| Nerst voltage (one cell) [En] | 1.115 V |
| H2 (Nominal hydrogen) | 99.92% |
| O2(nominal Oxidant) | 1.813% |
| Fuel (nominal Consumption | 15.22 slpm |
| Air | 36.22 slpm |
| The value foe current exchange [i0] | 0.027318 A |
| [Alpha] | 0.308 |
| Signal fuel composition [x_H2] | 99.95% |
| Signal Oxidant composition [y_O2] | 21% |
| Flow rate H2 [fuelFr]Nominal | 12.2lpm |
| Flow rate H2 [fuelFr] Maximum | 23.46 lpm |
| Flow rate O2 [AirFr]Nominal | 2400 lpm |
| Flow rate O2 [AirFr] Maximum | 4615 lpm |
| Temperrator [T] | 328 Kelvin |
| [Pfuel] | 1.5 bar |
| [PAir] | 1 bar |
| Initial value (Vref) | 60 V |
| Final value (Vref) | 80 V |
| Sample time | 5e-7 |
| Base frequency (Modulation) | 50HZ |
| Amplitude | 1 |
| Triangle signal | 22KH |
| Load Inductance | 50000e-6 μ H |
| Resistance Ron (MOSFET) | 0.1 Ω |
| Diode resistance (Internal) Rd | 0.01 Ω |

| | |
|--------------------------------------|----------------|
| Diode Inductance (internal) L_{on} | 0 H |
| Resistance RC (Snubber) | $1e5\Omega$ |
| Capacitance filter (output) | $100e-6\mu F$ |
| Load resistance | 20Ω |
| Proportional (PI) | 0.1 |
| Integral (PI) | 5 |
| Gain parameter value (PI) | $\frac{1}{80}$ |

Table 3 parameter from whole system

5.2.2 The fuel cell stack operation

The table above shows the value for the operation of the system. The fuel cell stack as input voltage (V_{in}) of CSI for single phase system the current and the power (voltage) from the fuel cell in Fig (16) characteristic curve present. The connected vehicle present on the fig (17)

The total current = 52.24 A

The total power = 1.26 KW

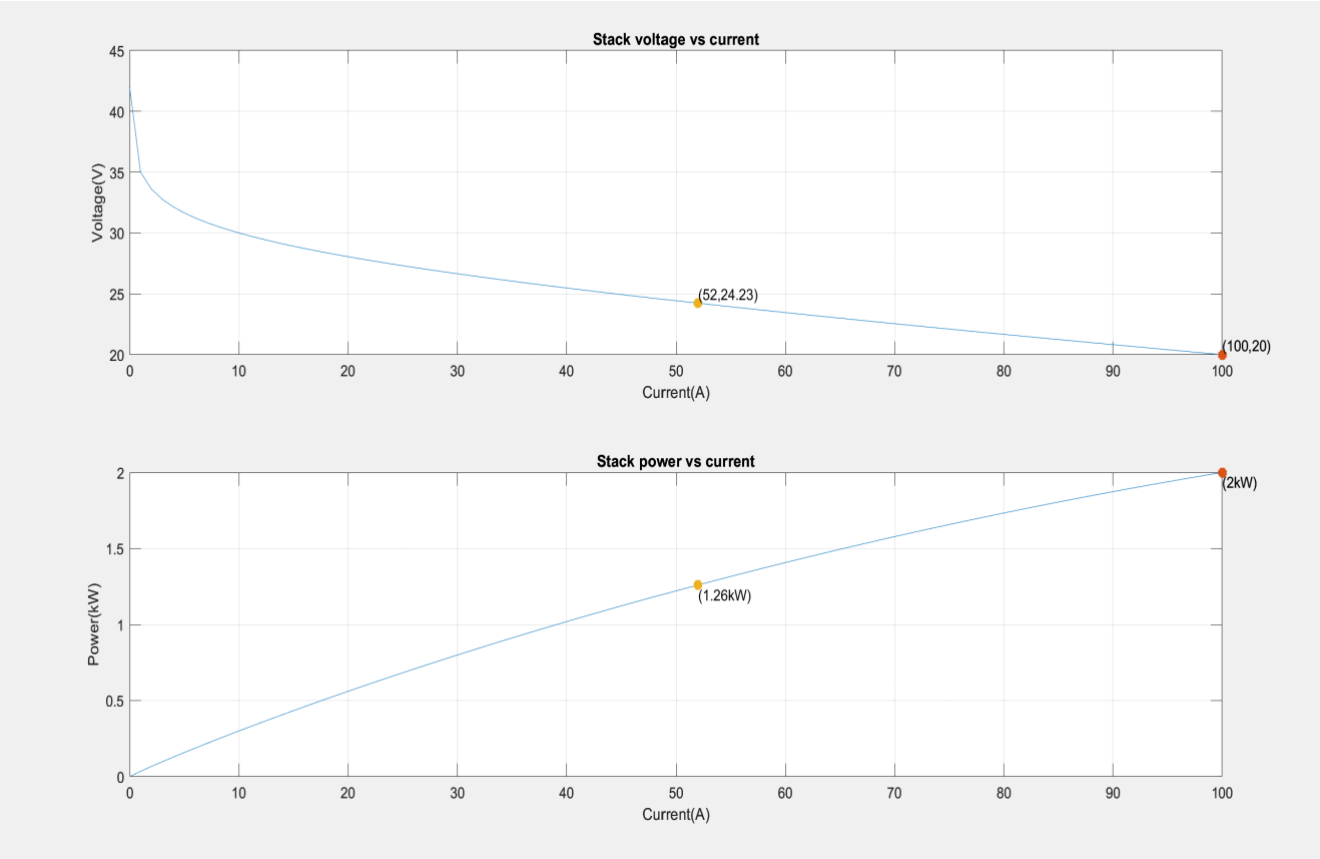


Figure 16 Characteristic curve

The fuel cell component contains thirteen logic signals for all the parameters factors **including the current and the voltage of the stack. Present on Fig (17) and Fig (18)**

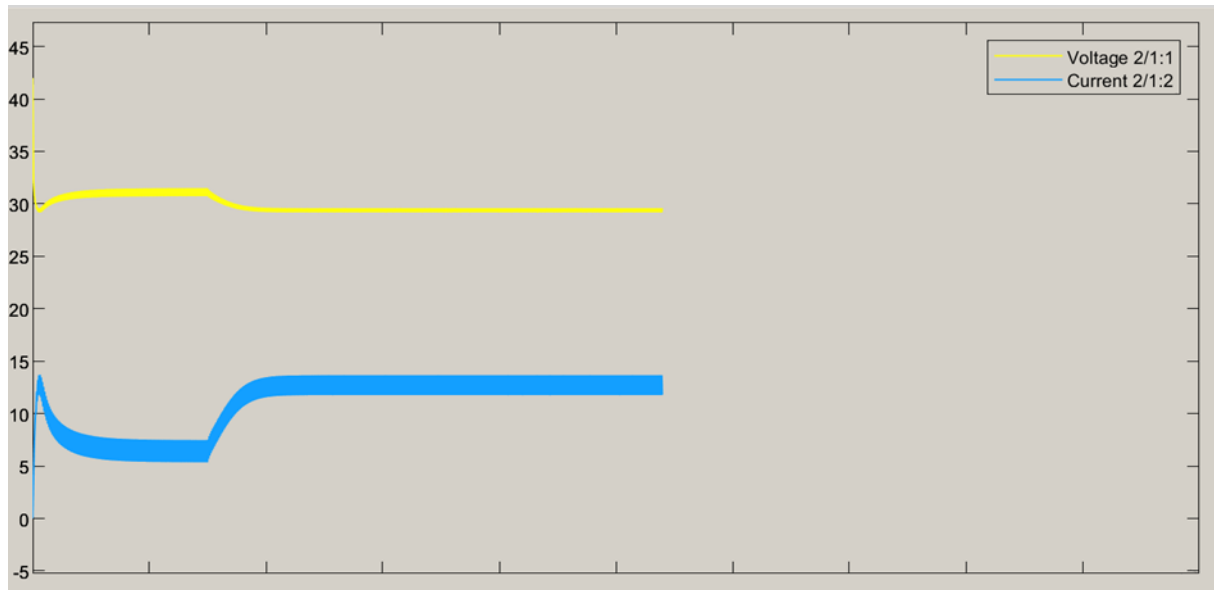


Figure 17 Output from fuel cell

The output for fuel cell

- 1) The output voltage $V = 75V$
- 2) The total power $P_t = 1.26 \text{ KW}$
- 3) The total current $I = 75 \text{ A}$ With PI controller with gain parameter, $(\frac{1}{80})$.
- 4) The Efficiency $\eta = \frac{\text{Wheel Energy}}{\text{Fuel Input Energy}}$ (6) [43]
- 5) Voltage Root Mean Square $V_{\text{rms}} = \sqrt{3} \frac{v_i}{m_a}$ (7) [44]

V_{rms} is the output RMS line-to-line voltage in PWM-CSI. [44]

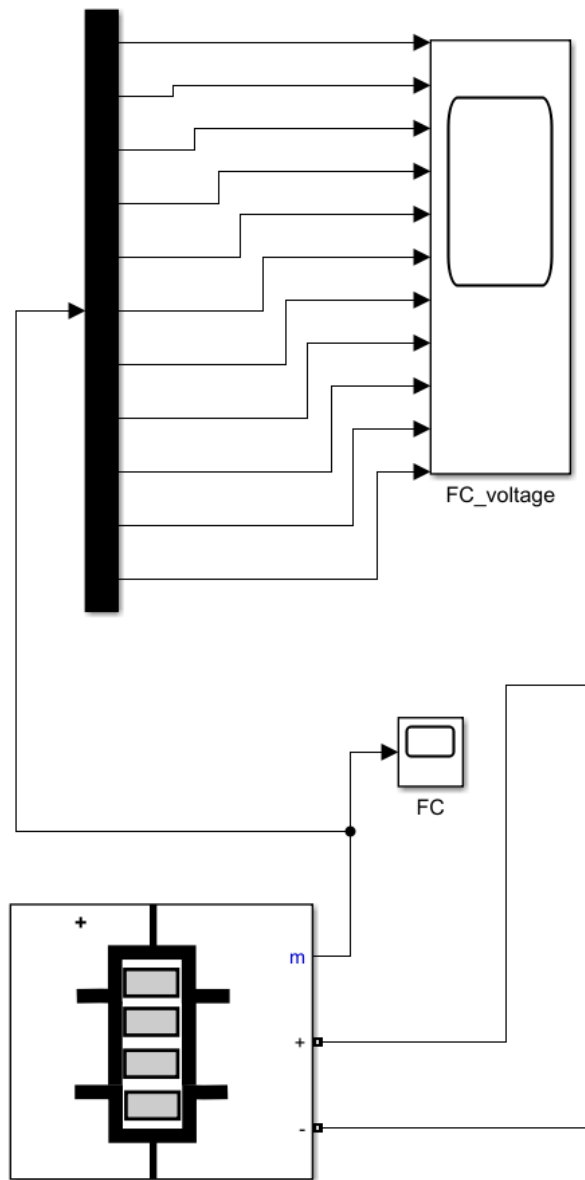


Figure 18 Fuel cell from simulation

5.2.2.1 Mathematical model for practical fuel cells

$$E_{o_c} = K_c E_n$$

$$i_0 = \frac{zFk(P_{H_2} + P_{O_2})\Delta v}{Rh} e^{-\frac{\Delta G}{RT}}$$

$$A = \frac{RT}{zaF} \quad [45](6)$$

R = 8.3145 J/(mol K).

F = 96485 A s/mol.

Z = Number of moving electrons.

E_n = Nernst voltage (dependent on the temperature and partial pressures of reactants and products inside the stack.)

a = Charge transfer coefficient (depends on the type of electrodes and catalysts within the fuel cell.

P_{H₂} = Partial pressure of hydrogen.

P_{O₂} = Partial pressure of oxygen.

k = Boltzmann's constant = 1.38 * 10⁻²³ J/K.

h = Planck's constant = 6.626 * 10⁻³⁴ J s.

Δv = Activation barrier volume factor (m³).

Δg = Size of activation barrier (computed assuming Δv = 1m³).

T = Temperature of operation (K).

K_c = Voltage constant at nominal condition and operation.

$$\begin{cases} U_{fH_2} = \frac{n_{H_2}^r}{n_{H_2}^{\hat{i}n}} = \frac{60000RTN i_{fc}}{zF P_{fuel} V_{lpm}(fuel)^{x\%}} \\ U_{fO_2} = \frac{n_{O_2}^r}{n_{O_2}^{\hat{i}n}} = \frac{60000RTN i_{fc}}{2zF P_{air} V_{lpm}(air)^{y\%}} \end{cases} \quad [45](7)$$

The rates of which hydrogen (U_{fH₂}) and oxygen (U_{fO₂}) are determined as shown above.

The 60000 constant comes from the conversion from the liter/min flow rate. (1 liter/min = 1/60000 m³/s)

The partial pressure values and Nernst voltage are proven as shown below in formula (8) and (9)

$$\begin{cases} P_{H_2} = (1 - U_{f_{H_2}}) x \% P_{fuel} \\ P_{H_2} = (w + 2y \% U_{f_{O_2}}) P_{air} \\ P_{O_2} = (1 - U_{f_{O_2}}) y \% P_{air} \end{cases} \quad [45](8)$$

$$E_n = \begin{cases} 1.229 + (T - 298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left(P_{H_2} P_{O_2}^{\frac{1}{2}} \right) \text{ when } T \leq 100^\circ C \\ 1.229 + (T - 298) \frac{-44.43}{zF} + \frac{RT}{zF} \ln \left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \right) \text{ when } T > 100^\circ C \end{cases} \quad [45](9)$$

P_{h_2O} = Partial pressure of water vapor inside the stack.

w = Percentage of water vapor in the oxidant.

The nominal rates of conversion of gases are calculated as seen below in formula (10)

$$\begin{aligned} U_{f_{H_2}} &= \frac{\eta_{nom} \Delta h^0(H_2O(gas)) N}{2zFV_{nom}} \\ U_{f_{O_2}} &= \frac{60000RT_{nom}NI_{nom}}{2zFP_{air_{nom}}V_{lpm(air)_{nom}} \cdot 0.21} \end{aligned} \quad [45](10)$$

η_{nom} = Nominal LHV efficiency of the stack.

$\Delta h^0(H_2O(gas)) = 241.83 \cdot 10^3$ J/mol.

V_{nom} = Nominal voltage (V)

I_{nom} = Nominal current (A)

$V_{lpm(air)_{nom}}$ = Nominal air flow rate (l/min)

$P_{air_{nom}}$ = Nominal absolute air supply pressure (Pa)

T_{nom} = Nominal operating temperature (K)

$$E_n = \begin{cases} E_n - K \left(U_{f_{o_2}} - U_{f_{o_2}^{(nom)}} \right) & U_{f_{o_2}} > U_{f_{o_2}^{(nom)}} \\ E_n & U_{f_{o_2}} \leq U_{f_{o_2}^{(nom)}} \end{cases} \quad [45](11)$$

$$K = \frac{V_u}{K_c \left(U_{f_{o_2}^{(peak)}} - U_{f_{o_2}^{(nom)}} \right)} \quad [45](12)$$

$$N = \frac{2.96485 \cdot V_{nom}}{241.83 \cdot 10^3 \cdot 0.55} \quad [45](13)$$

$$N = \frac{2.96485 \cdot 45}{241.83 \cdot 10^3 \cdot 0.55} = 65.28 = 65 \text{ cells.} \quad [45](14)$$

$$V_{lpm(air)_{nom}} = \frac{I_{nom} \cdot V_{lpm(air)_{max}}}{I_{end}} \quad [45](15)$$

$$V_{lpm(air)_{nom}} = \frac{133.3 \cdot 500}{225} = 297 \frac{\text{liters}}{\text{min}} \quad [45](16)$$

$$V_{lpm(air)_{nom}} = \frac{60000RT_{nom}NI_{nom}}{2zFP_{air_{nom}} \cdot 0.5 \cdot 0.21} \quad [45](17)$$

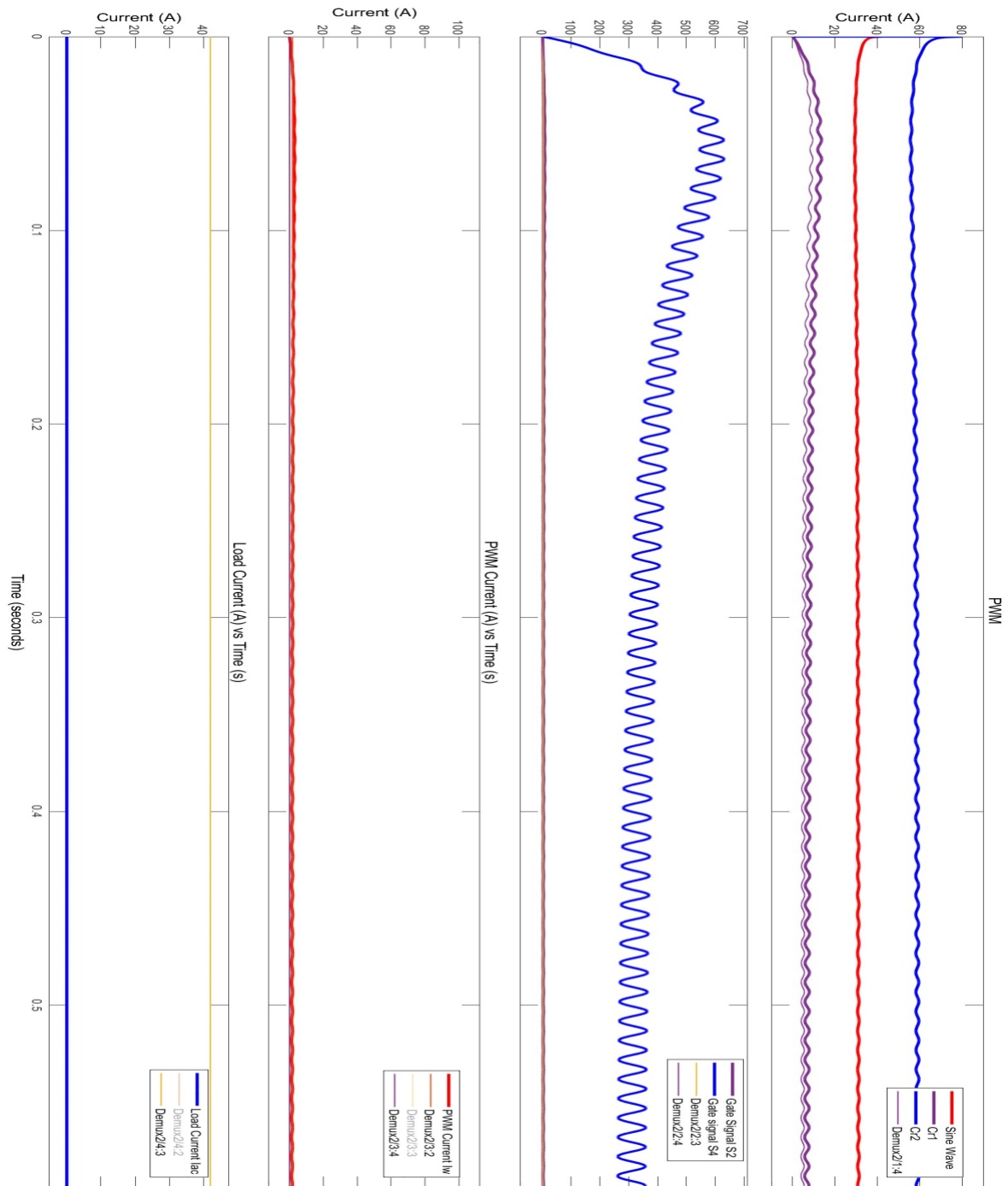


Figure 19 Signal from fuel cell

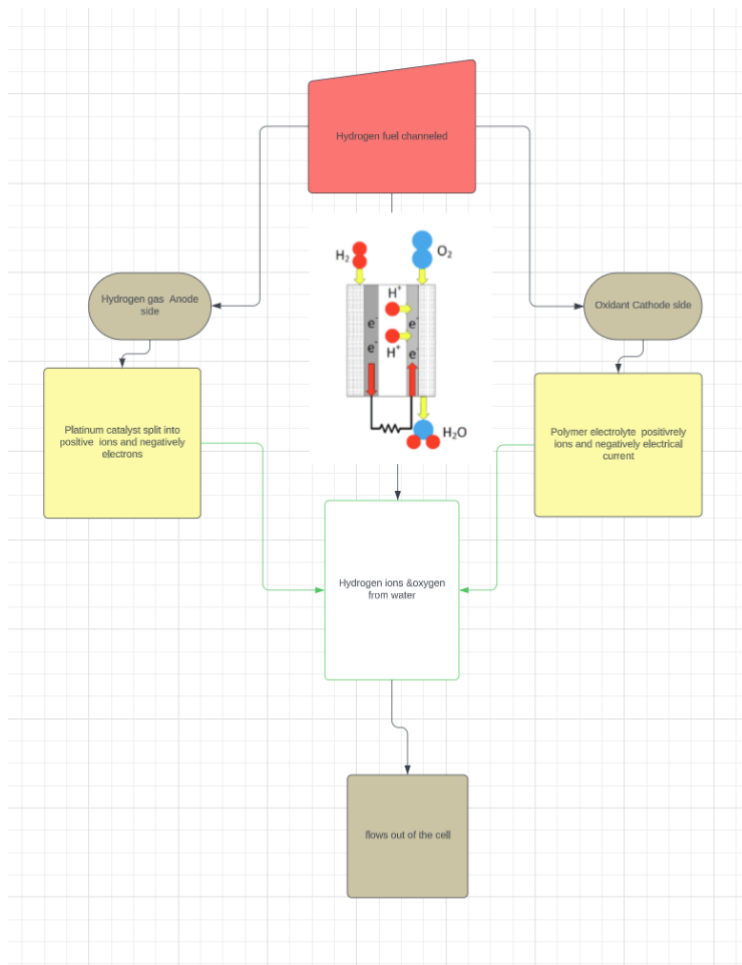


Figure 20 PEM process

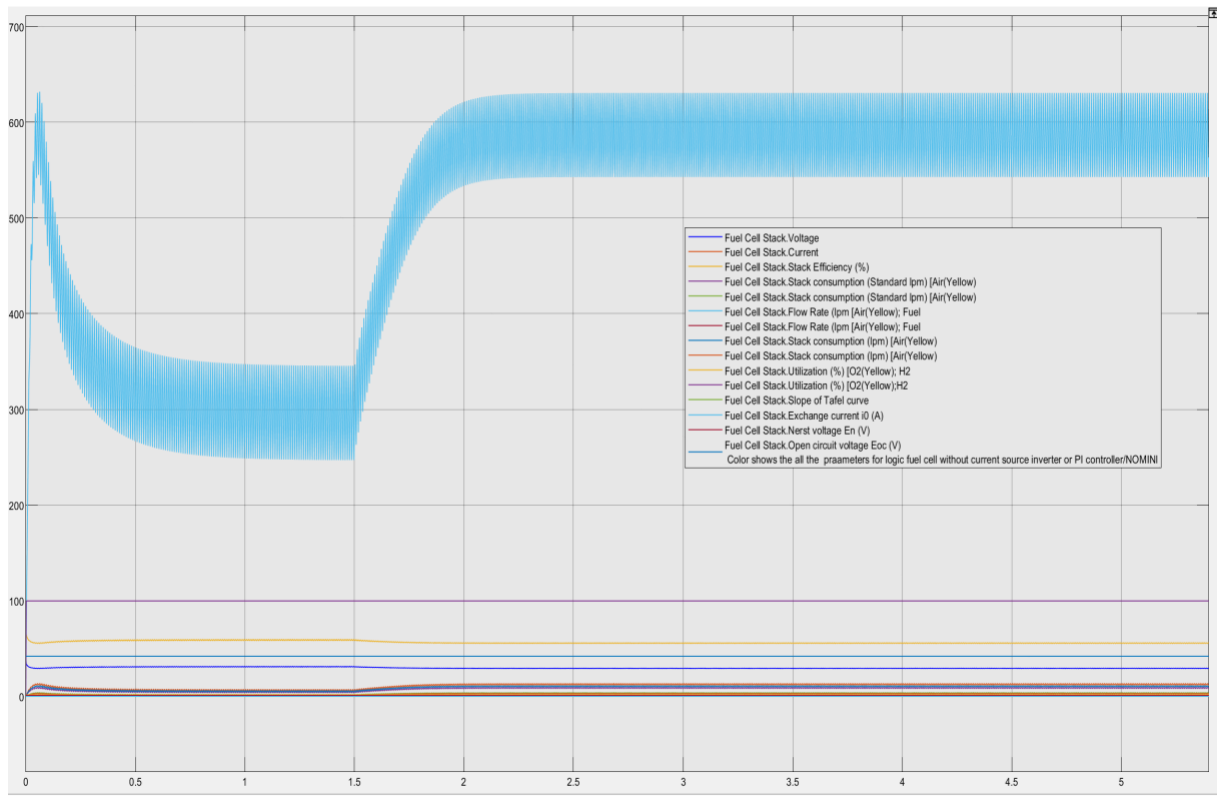


Figure 21 Nominal value from fuel cell

The figure above (21) shows the color of all the parameters for logic fuel cell without current sources inverter and without PI controller. This is all nominal value.

6. Analysis performance of a closed loop system

6.1 The voltage reference

- 1. The parameters simulated value for the close loop is:
- 2. Voltage reference: $V_{ref} = 160 \text{ V}$
- 3. Modulation index: $= 1$
- 4. Resistance: $R = 50 \Omega$
- 5. Capacitance $C = 100 \mu\text{H}$ constant
- 6. Output voltage $V = 120 \text{ V}$

The voltage cannot be beyond those values the V_{ref} is changed with the value for resistance for the performer close loop for the PI controller.

The voltage reference changed proportionally with the output parameters for the above shows when the resistance value 50Ω .

The upper limit value with $R = 50 \Omega$ is $V = 120$.

The results of the simulation present in Fig (22) and Fig (23) the max voltage of 120 V

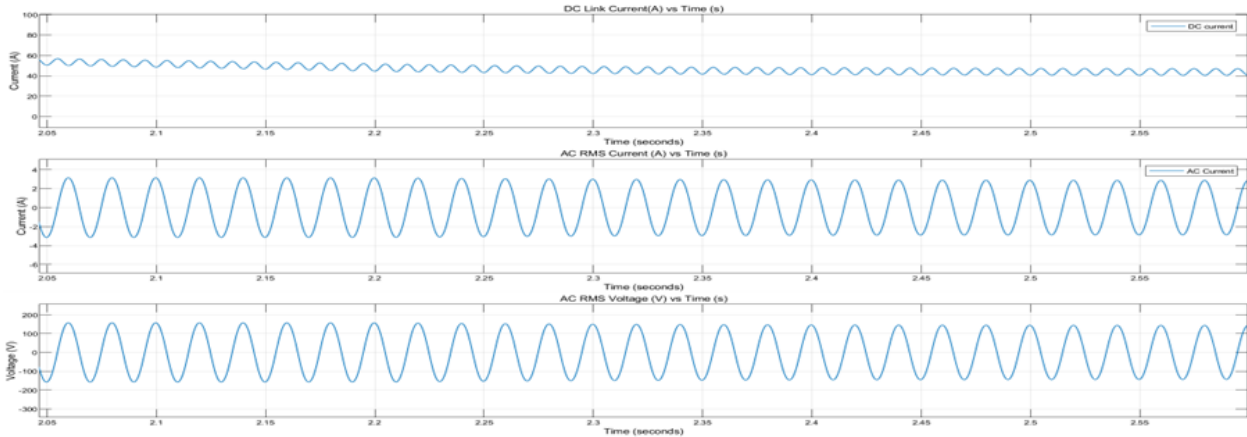


Figure 22 DC current

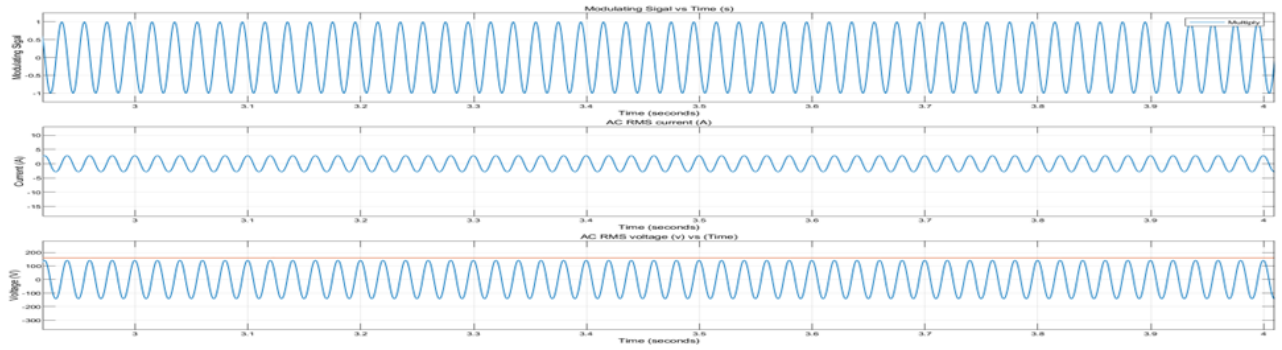


Figure 23 Modulation index

The parameters simulated value for the close loop is:

- 1) Voltage reference: $V_{ref} = 160 \text{ V}$ Modulation index $M_a = 0.7$
- 2) Resistance: $R = 70 \Omega$
- 3) Capacitance: $C = 100 \mu\text{H}$ constant
- 4) The output voltage $= 150 \text{ V}$

The increase in the value for resistance with a constant for the $V_{ref} = 160\text{V}$, $C = 100 \mu\text{H}$. The voltage gains value increase with $V = 150\text{V}$.

The upper limit for the voltage $V = 150\text{V}$

The results of the simulation present in Fig (24) the max voltage of 150V

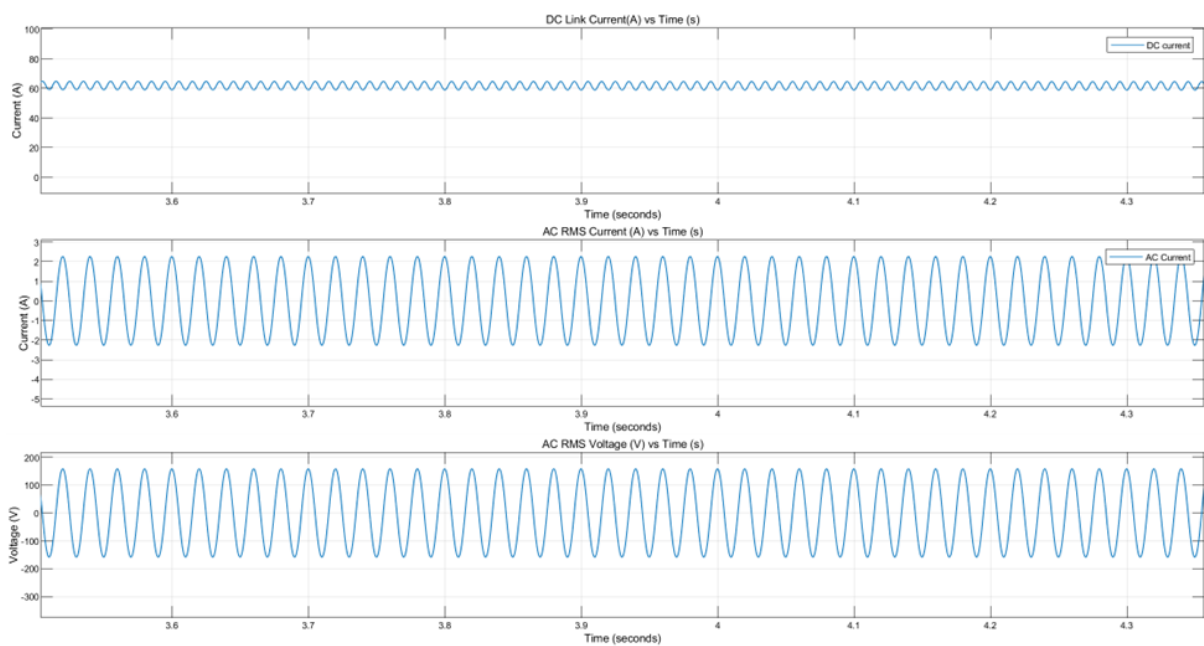


Figure 24 Current

The parameters simulated value for the close loop is:

- 1) Voltage reference: $V_{ref} = 160\text{ V}$ Modulation index $M_a = 0.7$
- 2) Resistance: $R = 20\ \Omega$
- 3) Capacitance: $C = 500\ \mu\text{H}$ constant
- 4) The output voltage $= 120\text{ V}$

The increase in the value for resistance with a constant for the $V_{ref} = 160\text{V}$, $C = 500\ \mu\text{H}$. The voltage gains value increase with $V = 120\text{V}$.

The upper limit for the voltage is $V = 120\text{V}$.

The results of the simulation present in Fig (25) the max voltage of 120V

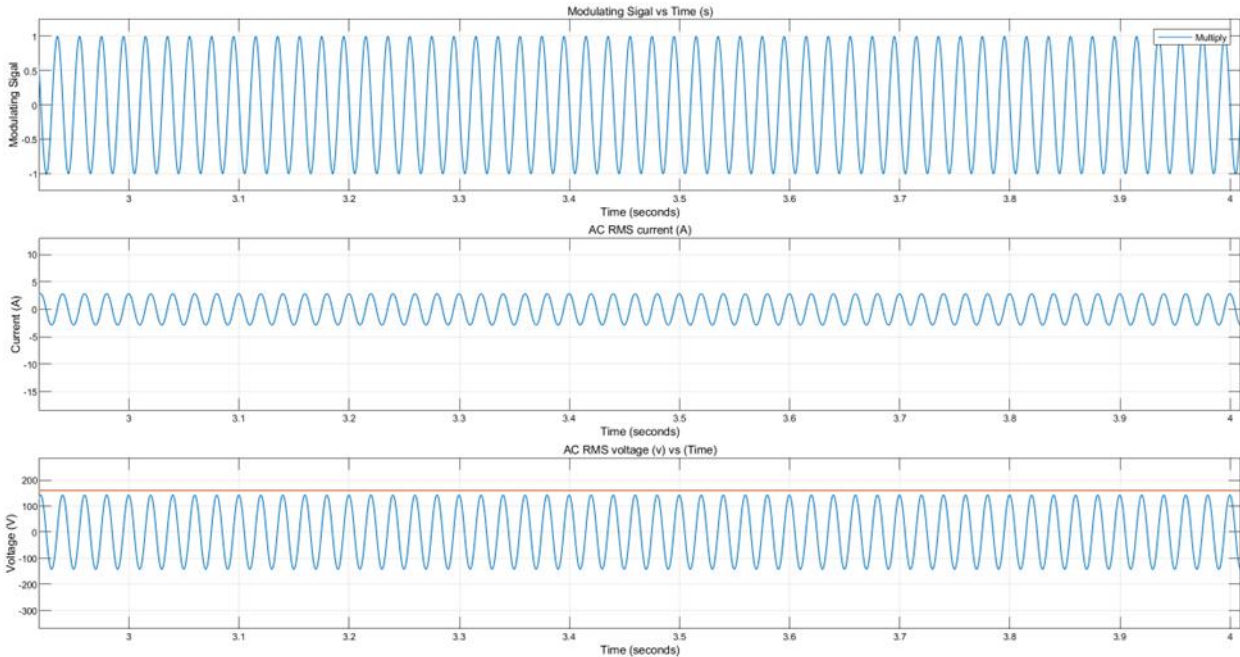


Figure 25 Results of simulation for $V_{out} = 120\text{V}$

Analyses performance for hole the system with open loop fig(26)

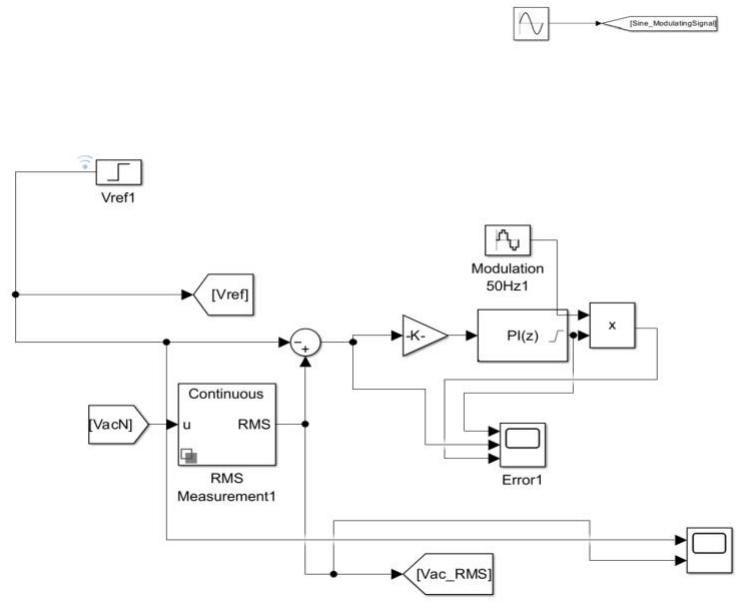


Figure 26 Open loop control system

6.2 Analysis for Whole system

6.2.1 The inductor (L):

For an inductor when we changed the value I microhenry it is no effect on the issue of that value for the load to low (100 μ H - 500 μ H) and the circuit will be open that means is disconnected, the circuit need to increase the value of the inductor to be connected electric circuit which current can be flow, therefore increasing for the value for the inductor it helps the system to be a close circuit to get the best result for the voltage. The value parameter for analyses is below: Tab (4)

| Inductors (L) | Voltage (V) | Resistance (R) | Amplitude (A) | Capacitance (C) |
|----------------------------|--------------|----------------|---------------|-----------------|
| 100 μ H to 500 μ H | Open Circuit | ----- | ----- | ----- |
| 100mH | 90V | 20 Ω | 0.7 | 700 μ F |
| 200mH | 95V | 20 Ω | 0.7 | 700 μ F |
| 300mH | 97V | 20 Ω | 0.7 | 700 μ F |
| 400mH | 98V | 20 Ω | 0.7 | 700 μ F |
| 500mH | 99V | 20 Ω | 0.7 | 700 μ F |

Table 4 Inductor value In analyses for an inductor with respect for the resistance R= 20 Ω and modulation index Ma = 0.7 with a low value for capacities C=

700 μ F and the frequency f = 50H, the voltage increases when the value for the inductor is increased, however, the value for the inductor in Simulink show at the in millihenry, an open loop for the ripple in DC show also in Simulink.

the value helps the circuit close to the current flow and the voltage can be calculated the result for the Simulink can show below.

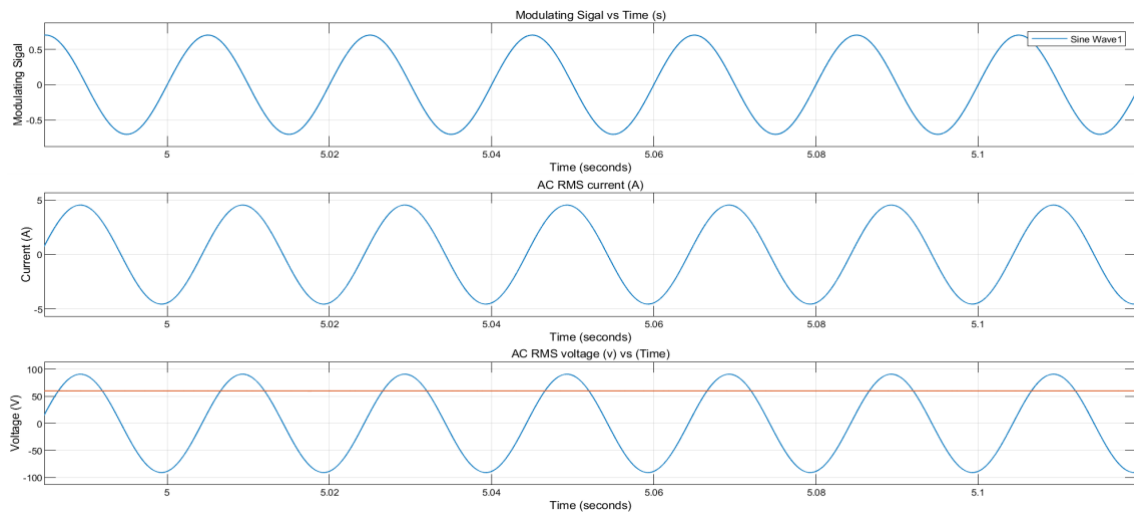


Figure 27 Resistance = 20 ohm

The value for fig (27):

- 1) Inductor: $L = 100e-3$
- 2) Resistance: $R = 20\Omega$
- 3) Modulation Index $M_a = 0.7$ $V_{ref} = 100V$
- 4) Output voltage $V = 91$
- 5) Capacitance $C = 700e-6$
- 6) The Maximum ripple upper peak = 41.5
- 7) The Minimum ripple lower peak = 41 The Ripple $100 \cdot \sqrt{\left(\frac{I_{rms}}{I}\right)^2 - 1}$

The maximum upper limit $V = 91V$

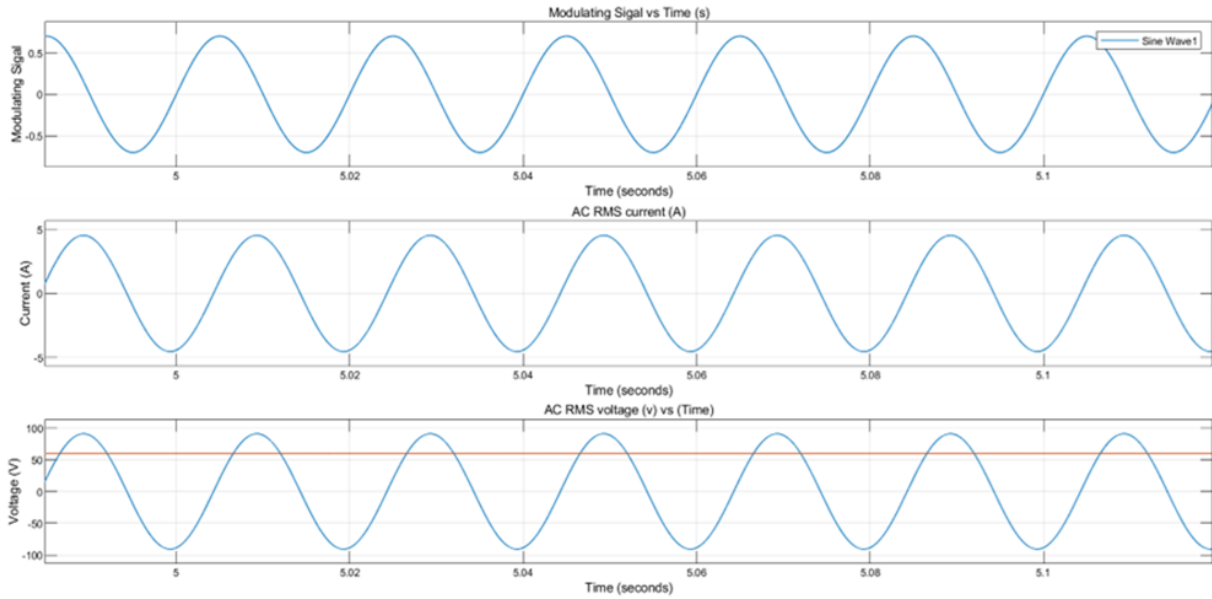


Figure 28 $V_{ref}=110$

The value for fig (28):

- 1) Inductor: $L= 200e-3$
- 2) Resistance: $R= 20\Omega$
- 3) Modulation Index $M_a= 0.7$
- 4) Output voltage: $95V$
- 5) The Maximum ripple upper peak = 41.5
- 6) The Minimum ripple lower peak = 41

$$\text{The ripple} = 100 \cdot \sqrt{\left(\frac{I_{rms}}{I}\right)-1}$$

The maximum upper limit $V=95$

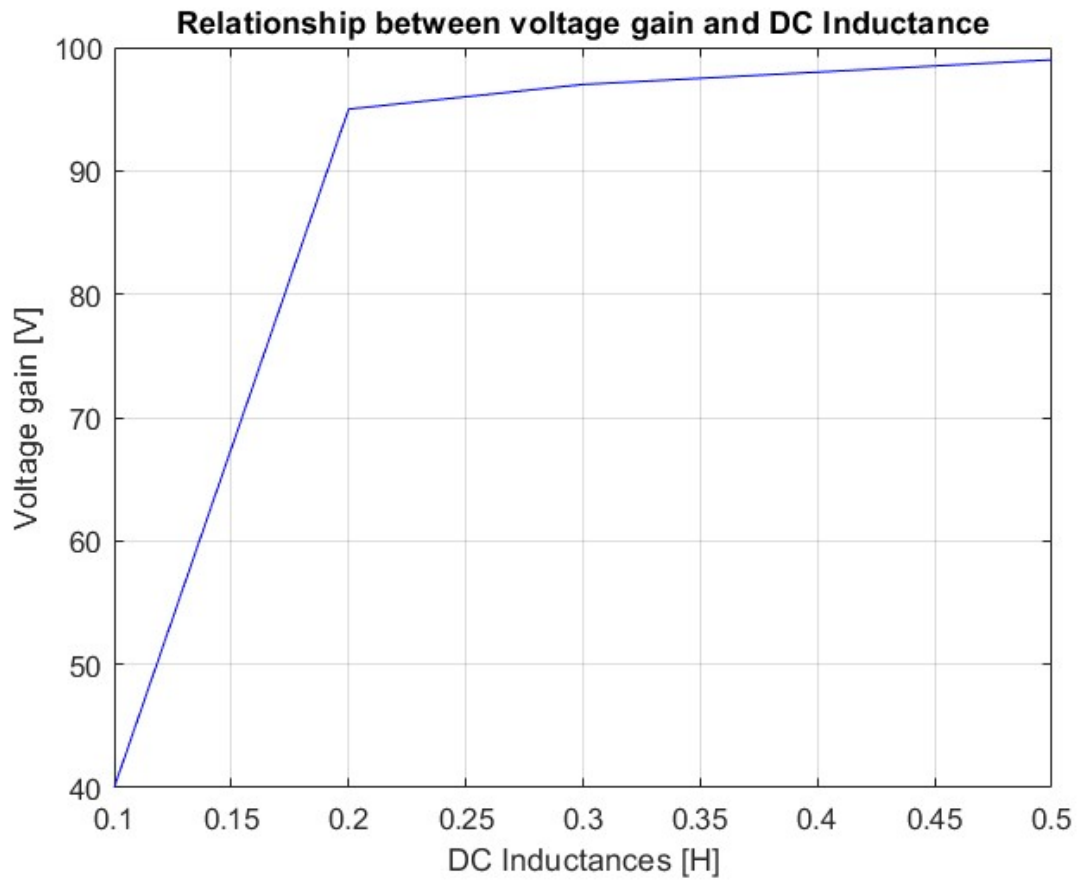


Figure 29 Relationship between voltage gain and DC inductance

6.2.2 The resistance (R):

In analyses for resistance with respect to the capacitor $C = 700\mu\text{F}$ and modulation index $M_a = 0.7$ with a low value for and the frequency $f = 50$, the voltage increases when the value for the resistance is increased, however, the value for the resistance in Simulink show at the in millihenry, an open loop for the ripple in DC show also in Simulink.

The value parameter for analyses is below: Tab (5)

In analysis for resistance with respect to the capacitor $C=700e-3F$ and modulation index $Ma=0.7$ with a low value for and the frequency $f=50$, the voltage increases when the value for the resistance is increased, however the value for the resistance in Simulink shows at the in millihenry, an open lop for the ripple in DC shows also in Simulink.

| Resistance r | Voltage(V) | Amplitude(A) | Capacitance C | Load (L) |
|---------------|------------|--------------|---------------|----------|
| 1 Ω | 25V | 0.7 | 700 μF | 200 mH |
| 10 Ω | 42V | 0.7 | 700 μF | 200mH |
| 20 Ω | 89V | 0.7 | 700 μF | 200mH |
| 100 Ω | 190V | 0.7 | 700 μF | 200mH |
| 1000 Ω | 241V | 0.7 | 700 μF | 200mH |
| 2000 Ω | 262V | 0.7 | 700 μF | 200mH |

Table 5 Resistance

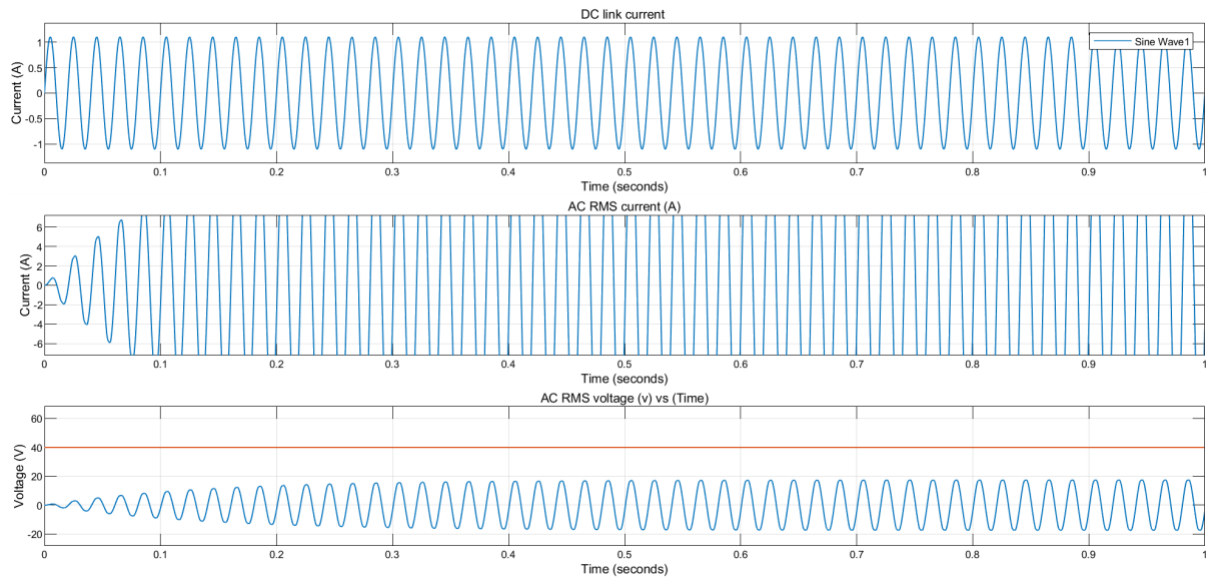


Figure 30 Resistance = 1 ohm

The value parameter for fig (30)

- 1) Inductor: $L = 200\text{mH}$
- 2) Resistance: $R = 1\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 25\text{V}$
- 5) Capacitance $C = 700\mu\text{F}$

The maximum upper limit is $V = 25\text{V}$.

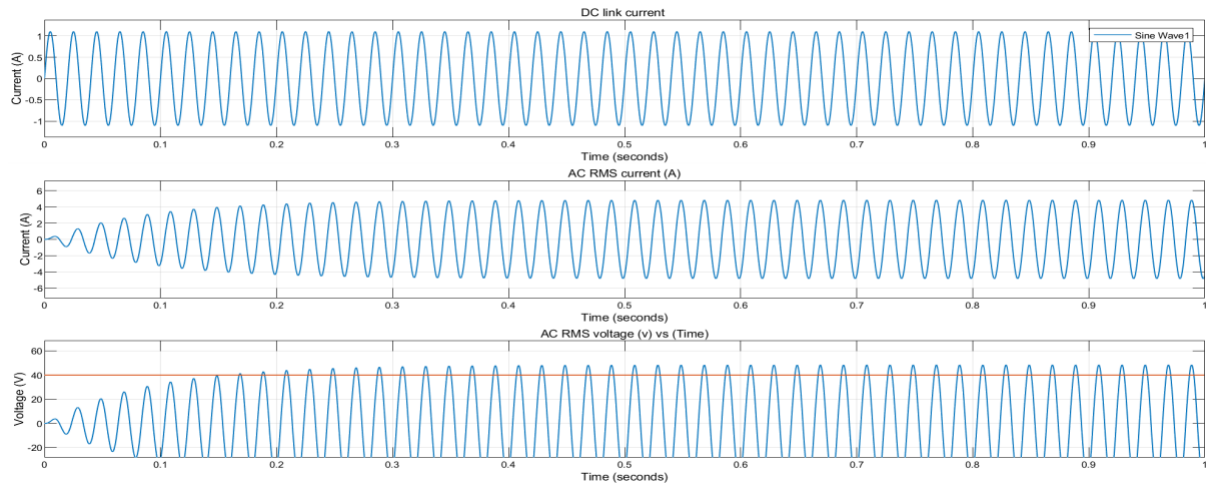


Figure 31 Resistance = 10 ohm

The value parameter for fig (31)

- 1) Inductor: $L = 200\text{mH}$
- 2) Resistance: $R = 10\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 42\text{V}$
- 5) Capacitance $C = 700\mu\text{F}$

The maximum upper limit is $V = 42\text{V}$.

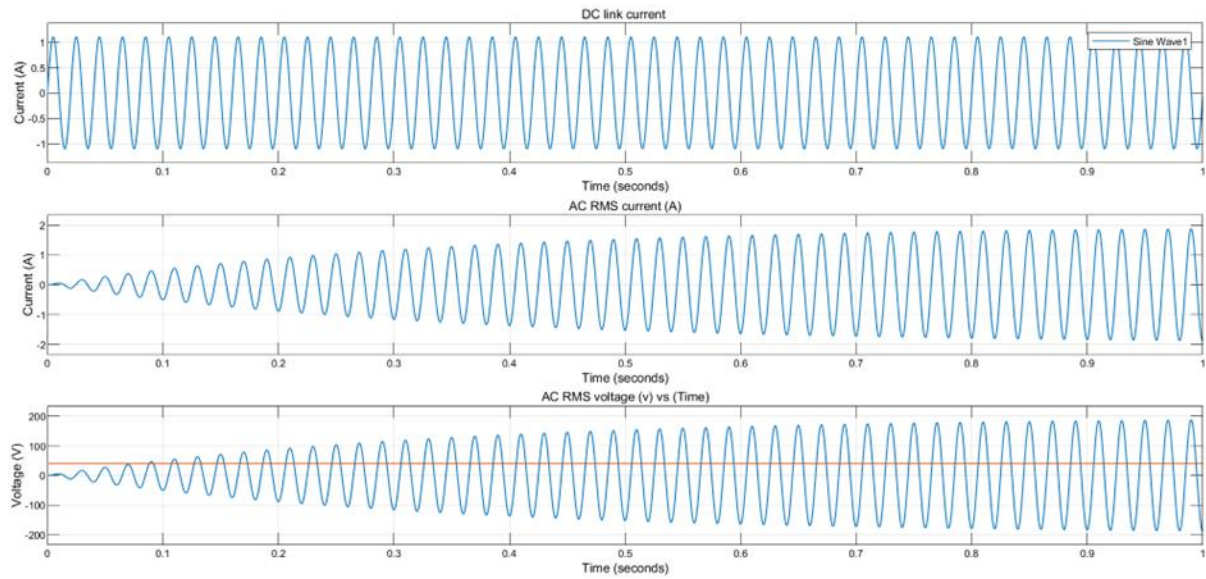


Figure 32 Resistance = 100 ohm

The value parameter for fig ()

- 1) Inductor: $L = 200\text{mH}$
- 2) Resistance: $R = 100\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 90\text{V}$
- 5) Capacitance $C = 700\mu\text{F}$

The maximum upper limit is $V = 90\text{V}$.

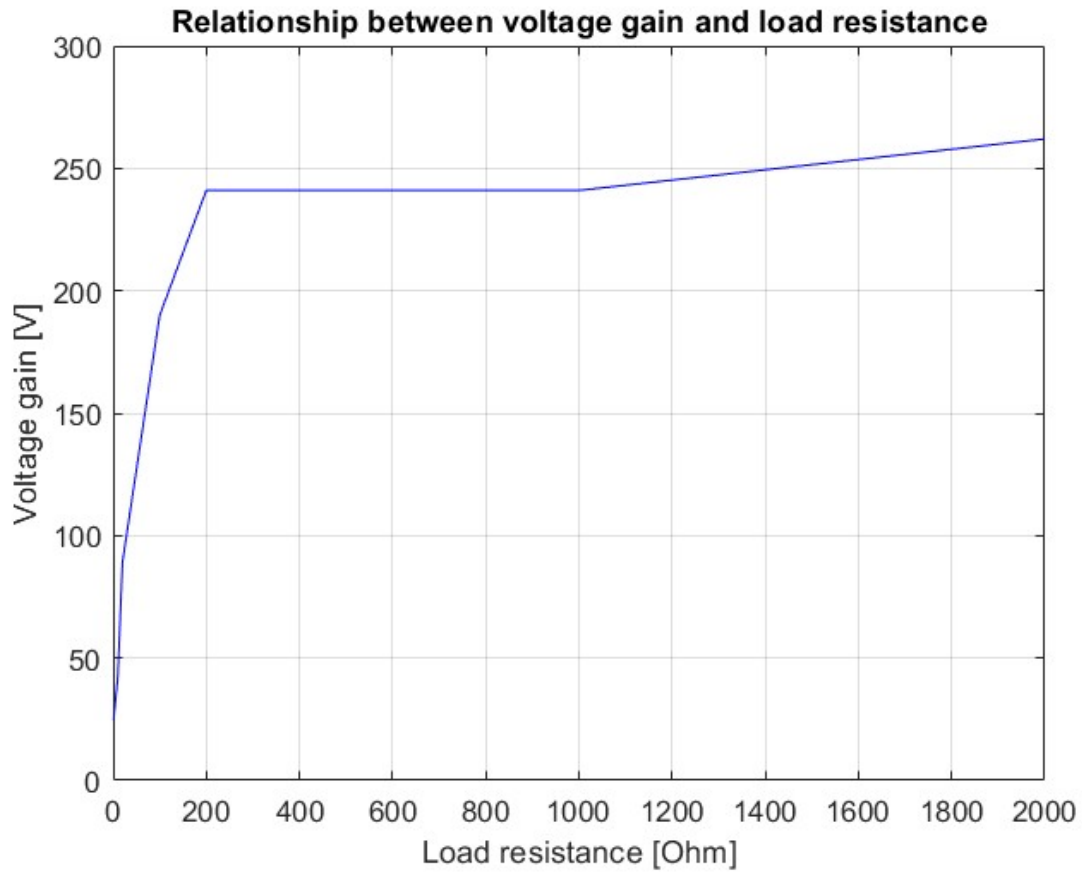


Figure 33 Relationship between voltage gain and load resistance

6.2.3 The capacitor (C):

The open loop analyses for a control system with capacitor filter parameter values are shown in the table above. The effect on the performance of the system of the voltage gain is

dependent on the value of the capacitance ratio equivalent direct proportion. Increase the value of capacitance which increases the value of voltage gain. The function for a component parameter is simulated and obtained through MATLAB simulation with setting up the value for modulation index (Amplitude), capacitance, and resistance are constant.

The value for the parameter shows blow: Tab (6)

| Capacities (C) | Voltage (V) | Resistant (R) | Amplitude (A) | Load (L) |
|--------------------|-------------|---------------|---------------|-------------------|
| 100e μF | 22V | 20 Ω | 0.7 | 300 μH |
| 200 μF | 25V | 20 Ω | 0.7 | 300 μH |
| 300 μF | 30V | 20 Ω | 0.7 | 300 μH |
| 400 μF | 39V | 20 Ω | 0.7 | 300 μH |
| 500 μF | 40V | 20 Ω | 0.7 | 300 μH |
| 600 μF | 43V | 20 Ω | 0.7 | 300 μH |
| 700 μF | 48V | 20 Ω | 0.7 | 300 μH |
| 1 mH | 60V | 20 Ω | 0.7 | 300 μH |

Table 6 Parameters for capacitor value

The result from the Simulink can show below:

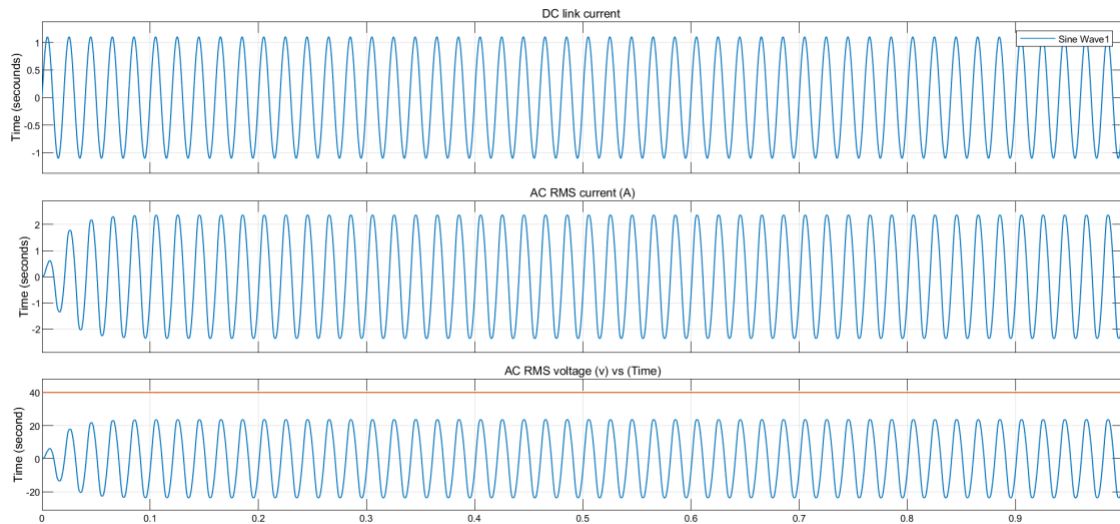


Figure 34 Capacitance = $100e-3$

The value parameter for fig (34)

- 1) Inductor: $L = 300\text{mH}$
- 2) Resistance: $R = 20\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 22\text{V}$
- 5) Capacitance $C = 100\mu\text{F}$

The maximum upper limit is $V = 22\text{V}$.

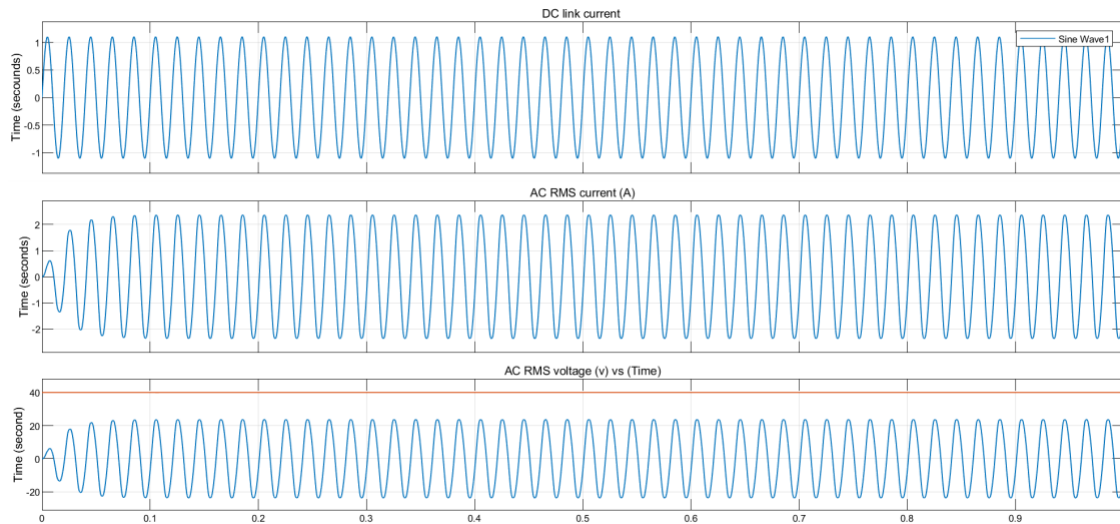


Figure 35 Capacitance = $200e-3$

The value parameter for fig (35)

- 1) Inductor: $L = 300\text{mH}$
- 2) Resistance: $R = 20\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 23\text{V}$
- 5) Capacitance $C = 200\mu\text{F}$

The maximum upper limit is $V = 23\text{V}$.

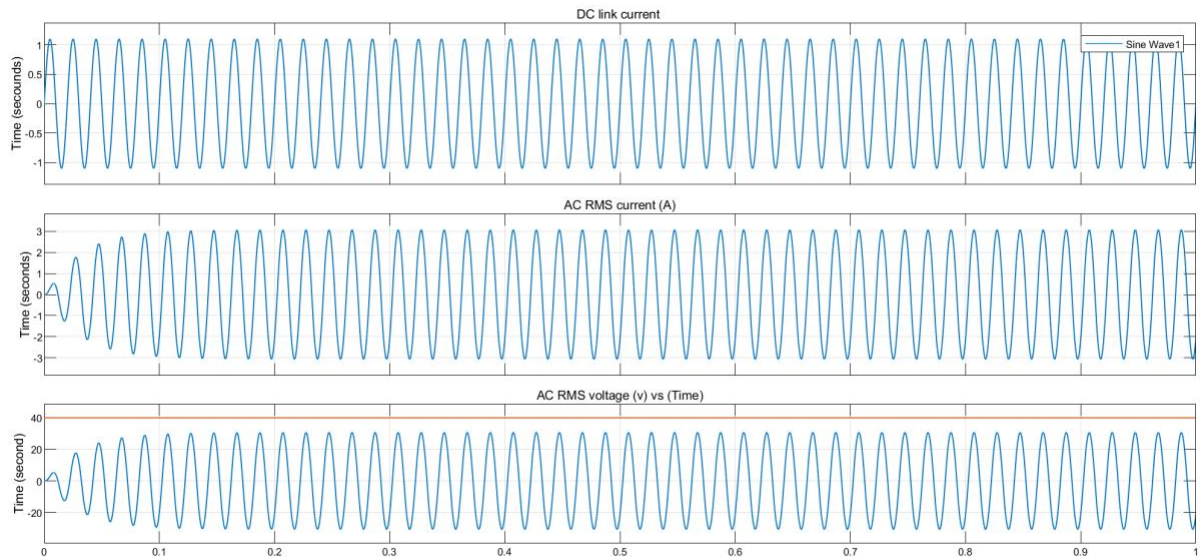


Figure 36 capacitance = $300e-3$

The value parameter for fig (36)

- 1) Inductor: $L = 300\text{mH}$
- 2) Resistance: $R = 20\Omega$
- 3) Modulation index $M_a = 0.7$
- 4) Output voltage $V = 30\text{V}$
- 5) Capacitance $C = 300\mu\text{F}$

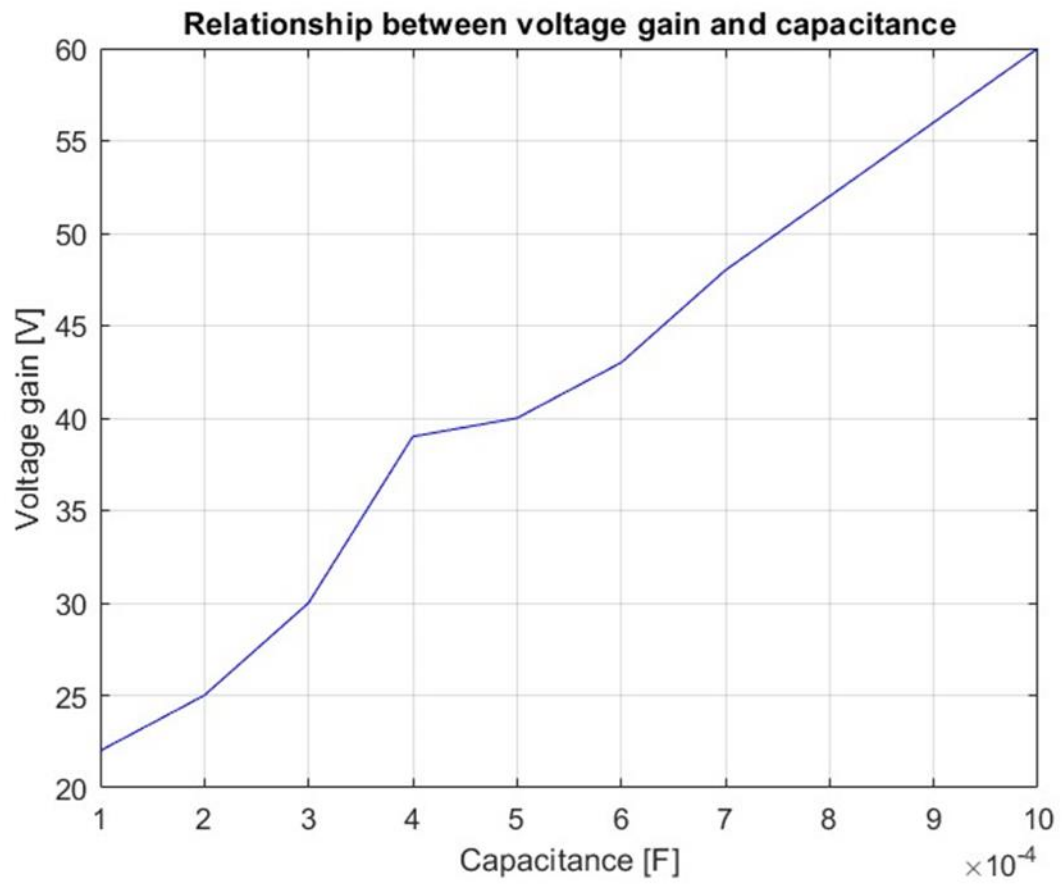


Figure 37 Relationship between voltage gain and capacitance

7. Discuss and conclude

In this thesis, the design for the current source inverter (CSI) topology with analyses with different parameters, with the open loop and closed loop system with the inverter and with fuel cell the component count, and system response, has been done. The answer for the equation in Chapter 5 is. Through the analysis of the current source inverter with a different value parameter for Inductor (L), and capacitor (C) Resistance (R). There are many values that has been tested and results showed in this project that between (160V-220V) had the most effect and the upper limit with the last testing 75V with resistance 20 Ω . The question about the effect of the resistance on the inductor is that it has effect on the value of the inductor, on the other hand if the inductor value increases so will the resistance value. The value effect for voltage gain is related and proportional to the same approximate value for the parameters, the modulation index (Ma) also known has a limit value of 1, therefore has no sufficient effect on the output voltage. The simulation was done on MATLAB.

8. Scope for Future Work

On further work, as mentioned on resources (Future) in Chapter 1.

The hardware testing is practically in vitro of inverter topology, with components that are related to the design. One issue is the issue about Fourier fast transform (FFT) because it must be calculated before designing the system.

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