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Solid oxide cell Stack voltage Emulator

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DEDICATION

To my late parent's memory.

To my late grandfather and guardian Issaka LABO

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Résumé

Au milieu de l'urgence croissante de la crise climatique, les technologies d'énergie alternative suscitent de plus en plus d'attention en raison de leur potentiel dans les applications de production d'énergie. Notamment, le système à cellules à oxyde solide (SOC) s'est imposé comme un acteur hautement efficace dans le processus de conversion d'énergie en différents types de carburants. Cependant, le coût intrinsèque et la sensibilité aux perturbations des tests ont souligné le besoin de solutions innovantes. Dans ce contexte, le développement d'un émulateur de SOC apparaît comme un catalyseur essentiel pour la recherche et l'expérimentation.

En effet, la création d'un émulateur SOC nécessite un effort multi-facette, exigeant la mise en œuvre de domaines électriques, thermiques et fluidiques. Cette étude est consacrée à la réalisation d'un émulateur de tension de pile. L'utilisation de KiCad, une suite complète de conception électronique open source, a facilité la mise en œuvre d'un circuit complexe qui englobe à la fois les domaines numériques et analogiques de l'émulation de tension.

L'objectif principal de cette étude était de concevoir et de simuler le comportement de l'émulateur de tension de pile par le biais d'une analyse minutieuse des composants numériques et analogiques, en vue d'obtenir une réplication précise et fiable des caractéristiques de tension de la pile.

Méthodologiquement, cette étude englobe la spécification du système, la conception du circuit, la recherche paramétrique des composants, une conception de schéma et de carte de circuit imprimé dans KiCad.

Les résultats de la simulation offrent des aperçus profonds sur les performances, la stabilité et les attributs de réponse du système. Ainsi, cette thèse tient la promesse d'influencer non seulement la conception des systèmes d'émulation SOC, mais aussi de contribuer au paysage plus large des solutions énergétiques durables.

Nos conclusions résonnent à travers des paramètres clés, y compris le gain de tension, la linéarité et l'analyse du temps de réponse transitoire. De plus, l'étude met en avant la mise en œuvre de mécanismes de protection englobant les limites de courant et la résilience contre les courts-circuits. En essence, cette recherche éclaire la voie pour exploiter le potentiel de la technologie des SOC grâce à des méthodologies d'émulation avancées.

Mots clés : cellules à oxyde solide, émulateur, power-to-x, KiCad

ABSTRACT

Amidst the growing urgency of the climate crisis, alternative energy technologies have garnered increasing attention for their potential in power generation applications. Notably, the solid oxide cell (SOC) system has emerged as a highly efficient player in the power-to-x process. However, the intrinsic cost and susceptibility to testing disruptions have underscored the need for innovative solutions. In this context, the development of a solid oxide cell emulator surfaces as a crucial enabler for research and experimentation.

Creating a SOC emulator entails a multi-faceted endeavour, necessitating the implementation of electrical, thermal, and fluidic domains. This study is devoted to the realization of a stack voltage emulator. Utilizing KiCad, a comprehensive open-source electronic design automation suite, facilitated the implementation of an intricate circuit that encompasses both the digital and analogue realms of voltage emulation.

The primary objective of this study was to design and simulate the behaviour of the stack voltage emulator through a meticulous analysis of digital and analogue components. The aim was to achieve accurate and dependable replication of stack voltage characteristics. The simulation results offer profound insights into the system’s performance, stability, and response attributes.

Methodologically, this study encompasses the design specification, circuit design, parametric search of components, a schematic and PCB design in KiCad. Our findings resonate across key parameters including voltage gain, linearity, and transient response time analysis. Additionally, the study underscores the implementation of protective mechanisms encompassing current limitations and resilience against short circuits.

In essence, this research illuminates a path toward harnessing the potential of solid oxide cell technology through advanced emulation methodologies. The outcomes of this thesis hold the promise of influencing not only the design of SOC emulation systems but also contributing to the broader landscape of sustainable energy solutions.

Keywords: Solid oxide cell, emulator, power-to-x, KiCad

ACRONYMS AND ABBREVIATIONS

AFC	Alkaline fuel cell
AWE	Alkaline water electrolyser
CO	carbon monoxide
CO2	carbon dioxide
COP	Conference of Parties
DAC	Digital to Analog Converter
DC	direct current
DMFC	Direct Methanol Fuel Cell
DSP	Digital signal processing
EDA	Electronic Design Automation
EEPROM	Electrically erasable programmable read-only memory
ERC	Electrical Rule Check
FC	Fuel Cell
FPGA	Field Programmable Gate Arrays
GND	Ground
H_2S	Hydrogen sulphide
H_3PO_4	Phosphoric acid
HIL	Hardware-in-the-Loop
HFCs	Hydrofluorocarbons
I2C	Inter-Integrated Circuit
IEEE	Institute of Electrical and Electronics Engineers
IJPEDS	International Journal of Power Electronics and Drive Systems
ISP	In-system programming
KOH	Potassium hydroxide
LiAlO2	Lithium and potassium carbonate
MATLAB	Matrix Laboratory
MCFC	molten carbonate fuel cells
N_2O	nitrous oxide
NaOH	Sodium hydroxide
OH	Hydroxide

PAFC	phosphoric acid fuel cells
PCB	printed circuit board
PEMEC	proton exchange membrane electrolyser Cell
PEMFC	proton exchange membrane fuel cell
PI	proportional integral
PMW	Pulse Width Modulation
P2X	Power-to-X
PVs	Photovoltaic
RE	Renewable Energy
SF6	Sulphur hexafluoride
SMD	Surface Mounted....
SOC	Solid Oxide Cells
SOEC	Solid Oxide Electrolyser Cells
SOFC	Solid Oxide Fuel Cell
SPICE	Simulation Program with Integrated Circuit Emphasis
U.N.F.C.C.C.	United Nations Framework Convention on Climate Change
USART	Universal synchronous asynchronous receiver transmitter
Y_2O_3	Yttrium oxide
YSZ	Yttria stabilized Zirconia
ZrO2	Zirconium dioxide

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GENERAL INTRODUCTION

General Introduction

Humankind has observed tremendous evolution in term of technologies during the past centuries. The world population growth, territorial expansions, technological innovations, rapid transformation of economies, emergency of urban areas and transformation of the global science system leads to the so-called industrial revolution. It is characterized by the creation of machines and engines to ease human life by the mechanization of the different sectors like transport, agriculture and industries. The fuel used to power these technologies was mainly coal, oil and Natural gas (Wadanambi & Wandana, 2020). Nevertheless, in the 1965 scientists have notice some modification in the Global temperature. This changing in the Global temperature leads to the term “Climate Change”, According to U.N.F.C.C.C. (1992), climate change means "a change of climate, attributed directly to human activity. Global warming gradually increased because of the anthropogenic greenhouse gasses trapped in the atmosphere. The effect can be attributed to gases like carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and water vapor (Wadanambi & Wandana, 2020),(Dincer, 2000).

Greenhouse gas is a gas that can trap the infrared radiation emitted by the Earth at the surface and emits it back. Without the natural greenhouse effect, the Earth would be an inhospitably cold place, with an average temperature well below the freezing. The natural greenhouse effect is responsible of keeping the temperature of the Earth around 30 °C, making the earth habitable (*FAQ*). However, it is important to note that the balance of greenhouse gases is delicate and human activities, such as burning fossil fuels, contribute to their exponential increase (Jain, 1993).

After several COP (Conference of parties) we know what to do to save our planet and leave a secure place for future generations. Burning fossil fuels to produce electricity for our households, powering our cars or powering our industries with coal, oil, and natural gas will just increase the amount of CO_2 in the atmosphere leading to the Earth’s destruction. Shifting from these carbon-based energy sources to renewable energy sources, called energy transition Abas et al., (2015), is not possible without investing in the research and development of the renewable technologies.

By definition, renewable energy is the energy that is renewed in a short cycle, such as solar energy, biomass energy, wind energy, geothermal energy, tidal energy, and hydropower energy. These forms of energy are clean and accessible for all. In contrast to the fossil fuel, the sources of renewable energy are abundant and are more to the environmental friendly (Mohtasham, 2015).

One major challenge for the replacement of fossil fuels with renewable energy sources is the long-term storage of electrical energy (Kruse et al., 2021). Because renewable sources like wind and solar depend strongly on the weather conditions. Solar panel uses photons from solar radiation to produce electricity, so during the night or under cloudy sky it is quite impossible to produce electricity from panels. Wind turbines convert the kinetic energy in the wind to electricity, meaning that we cannot have electricity during period of low wind speed. This dependence of solar energy and wind energy on the weather conditions is called Intermittency. In order to solve the problem of intermittency, energy storage systems are needed to store the excess of electricity under favourable weather conditions (Barton & Infield, 2004).

The storage of electricity directly is one of the challenges in modern science. It can only be stored in a very small amount trough the usage of various types of capacitors or in electromagnetic superconducting coils, and both of these technologies are costly. Rather, it has to be converted into another form of Energy for storage. The alternative types of energy are: (i) potential energy (pumped-hydro, compressed-air); (ii) kinetic energy (usually in the form of flywheels); (iii) thermal energy (hot water, fused salts); and (iv) chemical energy (generally as hydrogen, methanol or as chemicals in batteries). Among these technics of storing electricity, the chemical energy storage through hydrogen is the most efficient and promising technic in the context of sustainable energy development (Dell, 2001).

Hydrogen is an energy carrier. The fact that it is clean, has high energy content on mass and can be used in transportation, agriculture, industry, heating and electricity generation makes it one of the best fuel for future energy system (Sundén, 2019). It can be produced in several ways like hydrocarbon reforming, hydrocarbon pyrolysis, electrolysis, and reforming of biomass fuels (Nikolaidis & Poullikkas, 2017). Depending on the source of energy, the feedstock and CO_2 emission, we have three major types of hydrogen: grey Hydrogen, blue hydrogen and green hydrogen (Hermesmann & Müller, 2022).

Grey hydrogen is made using fossil fuels like natural gas, oil and coal, which emit CO_2 into the air as they combust. The blue variety is made in the same way as the grey, but carbon capture technologies prevent CO_2 being released, enabling the captured CO_2 to be stored deep underground or utilized in industrial processes. Finally, green hydrogen is the cleanest variety, producing zero carbon emissions. It is produced using electrolysis powered by renewable energy, like wind and solar, to produce a clean and sustainable fuel (Lagioia et al., 2023).

For the green hydrogen to be produced and used as fuel, electrolysers and fuel cells are needed.

By definition an electrolyser is an electrochemical device that uses electricity to split water molecule into hydrogen and oxygen. On the other hand a fuel cell is considered the reverse of an electrolyser because it generate electricity by electrochemical reaction in which oxygen and hydrogen are the reactants and water is formed as the product (Sundén, 2019). Several types of electrolysers and fuel cell exist. Some major types are presented in the sections below. Among the Available technologies , Solid Oxide Cells (SOC) systems, mainly electrolyser and fuel cell constitute the best option as they provide one of the highest levels of efficiency for the production of hydrogen from water and its conversion back to electricity (Kruse et al., 2021).

SOC systems are still under research and development (R&D), making them very expensive for manufacturing. In the recent years, SOC systems have seen very great advancements in term of R & D (Hauch et al., 2020; Minh et al., 2017). Research has also proved that an SOC system can be used for both electrolysis and fuel cell operation Frank et al., (2018); Kruse et al., (2021); Peters et al., (2021) making it the first system to achieve such advancement. These systems will play a key role in the energy transition and climate change mitigation, because despite the production of green Hydrogen, we can also do a co-electrolysis, though reduce the amount of CO_2 in the atmosphere(Sitte & Merkle, 2023).

However, SOC systems are still under Research and development (R&D), and the high cost of cells make it difficult to use in the research purpose. Testing the actual fuel cells for design and control of power electronic converters, optimization, diagnosis and parameter estimation is not always viable because a fault with testing procedure can result in expensive damage to the cell Stack (Gebregergis & Pillay, 2007). Therefore, the use of emulator that can mimic the static and dynamic characteristic of SOC stacks will be of a tremendous help for researchers and developers. The target of this study is the development of a stack voltage emulator as part of a complete SOC stack emulator. The specific research objectives include:

1. Design specifications Planification of the function of the Circuit
2. Parametric research of electronic components
3. Understand more about kiCad and Creation of Proper schematic Using KiCad

4. Design and order the PCB (printed circuit board) of the voltage Emulator.

This study is divided into three chapters and is organized as follows:

- Chapter 1 introduces the literature review, where the Background of electrolysers and fuel cells is presented, and some studies on different kind of emulators.
- Chapter 2 explains the methodology followed, and present all the materials used for the implementation of our Circuit.
- Chapter 3 exposes the results and discussion of the simulation in KiCad.

CHAPTER I.

LITERATURE REVIEW

I.1 Background of Fuel cell and Electrolyser

I.1.1 Electrolysis of water

When talking about electrolysers, the first thing that crosses our mind is that they have been developed during the recent years. Because today, in all countries everywhere in the world, new projects are being developed in the way of promoting this technology for the hydrogen economy. However, this technology existed long before humanity started observing global warming. The history starts as early as the first industrial revolution, when in the early 1800s two scientists, William Nicholson and Anthony Carliste discovered that the water molecule could be split into its two components, hydrogen and oxygen by applying electrical current (Kreuter, 1998; Sun et al., 2018).

Since the 1900s, more than 400 Alkaline water electrolysers were in operation and in 1939 the first large water electrolysis was built, followed by the proton exchange membrane electrolyser (PEM) in the 1950s and its commercialization by General Electric in 1966. Last but not the least, the Solid Oxide electrolyser, one of the most promising technologies was first developed in the 1960s mainly in the United States and Germany(Peters et al., 2021; Ursua et al., 2012).

I.1.1.1 Working principle of Electrolyser

An electrolyser is an electrochemical device that uses electricity to split water molecule into hydrogen and oxygen, the process is called water electrolysis. Like all the electrochemical devices, an electrolyser is composed of a basic unit call electrochemical cell. An electrochemical cell is composed of a positive and a negative electrode which are separated by an electrolyte. At the electrode are occurring respectively Oxidation and reduction. Oxidation is when a chemical species releases electrons to another chemical species and reduction when the chemical species receives electrons(Sundén, 2019).

For the reaction to occur, the two electrodes must be connected to a direct current (DC) supply. when enough voltage is applied to the cell, we have production of hydrogen at the cathode and oxygen at the anode(Smolinka et al., 2015). The **Figure 1**depicts a principal sketch of unit cell of an electrolyser.

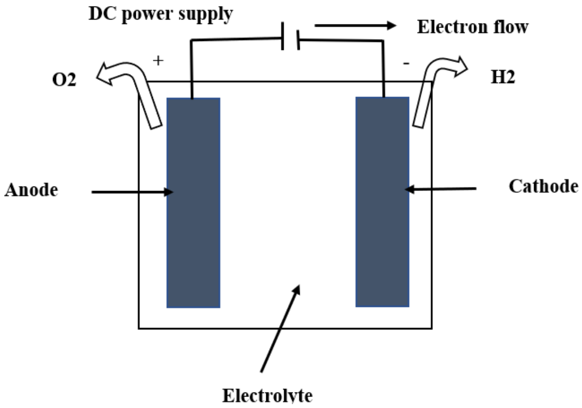

Figure 1: Unit cell of electrolyser

I.1.1.2 Electrolyser technologies

With the rising demand of green hydrogen due the climate crisis, several types of electrolysers are being developed. The market has exposed with high demand of Hydrogen-powered products. The tree most common technologies today are Alkaline water electrolyser(AWE), PEM electrolyser , and SOEC(Mayyas & Mann, 2019; Ursua et al., 2012). The **Table 1** gives a short summary of these technologies and their main characteristics.

Table 1 : Majors technologies of electrolyser and characteristics(Ottosson, 2021; Shiva Kumar & Lim, 2022)

Parameters	Electrolyser Types		
	Alkaline	PEM	Solid Oxide
Electrolyte	KOH/NaOH	Solid polymer electrolyte (PFSA)	Yttria stabilized Zirconia (YSZ)
Operating temperature	$70 - 90℃$	$50 - 80℃$	$700 - 850℃$
Anode	$2OH^- \rightarrow H_2O + \frac{1}{2}O_2 + 2e^-$	$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-$	$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$
Cathode	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Voltage range	$1.4 - 3\ V$	$1.4 - 2.5\ V$	$1.0 - 1.5\ V$
Efficiency	$50\% - 78\%$	$50\% - 83\%$	89%(laboratory)
Development status	Mature	Commercialized	R & D

I.1.2 Fuel cell

The history of fuel cell starts just after the discovery of the electrolysers by William Nicholson and Anthony Carlisle in the 1800s. A scientist call Sir William Grove, in 1890 was conducting an electrolysis experiment and discovered accidently the possibility reversing the reaction. William Grove has disconnected the battery from the electrolyser and connected the two electrodes together, and he observed a current flowing in the opposite direction, consuming the gases of hydrogen and oxygen. Grove calls his device a “gas battery”. The gas battery was composed of platinum electrodes placed in test tubes of hydrogen and oxygen immersed in a dilute sulfuric acid.(Cook, 2002; Ortiz-Rivera et al., 2007)

The concept fuel cell appears in the in the 1950s by Francis Bacon, a chemical engineer at the University of Cambridge successfully produced the first practical fuel cell. The cell was an Alkaline version and uses alkaline electrolyte (molten KOH) instead of dilute sulfuric acid. Having

done a remarkable job, Bacon's work was licensed and adopted by NASA. After several corporations with industrial partners, NASA developed fuel cell generators for Space missions.
In 1960s, the PEMFCS and Alkaline were practically used in the Gemini and Apollo manned space programs. (Sharaf & Orhan, 2014) .The two technologies were followed by the creation of different types of fuel cells in the US, Germany, and Japan. The main reason why the developers focused on developing new technology was the problem of the Alkaline electrolyte. They have developed the technologies like solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), for terrestrial applications.(Cook, 2002)

I.1.2.1 Working principle of Fuel cells

The working principle of a fuel cell is the reverse of the one for Electrolyser. Therefore, they operate like batteries, consisting of an electrolyte placed between two electrodes: an anode and a cathode. In contrast with batteries, for the fuel cell the fuel is continuously supply. Hydrogen is supply through one electrode, and oxygen over the other, for the fuel to generate electricity, water and heat. Hydrogen fuel is fed into the "anode" of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode(Ortiz-Rivera et al., 2007). **Figure 2** illustrate a principal sketch of a unit cell of a fuel cell.

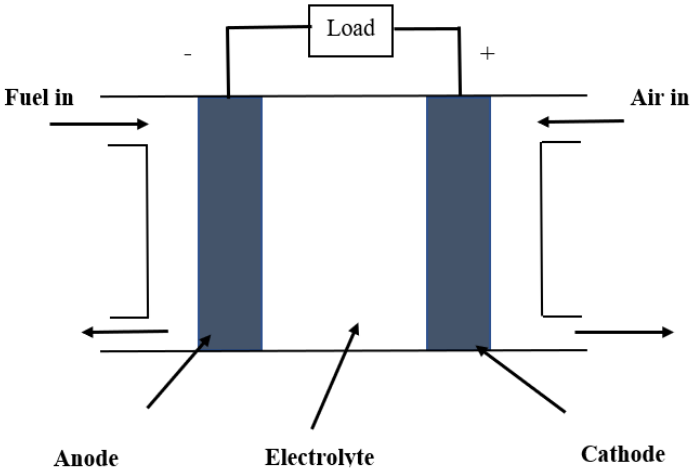

Figure 2 : Unit cell of a fuel cell

I.1.2.2 Fuel cell technologies

Fuel cells can be classified according to different characteristics. **Table 2** and **Table 3** describe a summary of the major types of fuels cell and their characteristics features like electrolyte, and operating temperatures.

Table 2 : Majors types of fuel cell (Kirubakaran et al., 2009; Sharaf & Orhan, 2014; Sundén, 2019)

Parameters	Fuel cell types		
	PEMFC	AFC	PAFC
Electrolyte	Solid polymer membrane (Nafion)	Liquid solution of KOH	Phosphoric acid (H3PO4)
Operating temperature (8C)	50-100	50–200	~200
Anode reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2(OH^-) \rightarrow 2H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$
Cathode reaction	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2(OH^-)$	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Charge carrier	H^+	OH^-	H^+
Fuel	H_2	H_2	H_2
Efficiency	40-50%	~50%	~40%
Cell Voltage	1.1 V	1.0 V	1.1 V
Advantages	High power density; quickstart up; solid non-corrosive electrolyte	High power density; Quick start up	Produce high grade waste heat; stable electrolyte characteristics
Drawbacks	Expensive platinum catalyst;sensitive to fuel impurities(CO, H2S)	Expensive platinum catalyst; sensitive to fuel impurities (CO, CO2, CH4, H2S)	Corrosive liquid electrolyte; sensitive to fuel impurities (CO, H_2S)

Table 3 : Majors types of fuel cell (Kirubakaran et al., 2009; Sharaf & Orhan, 2014; Sundén, 2019)

Parameters	Fuel cell types		
	MCFC	SOFC	DMFC
Electrolyte	Lithium and potassium carbonate (LiAlO2)	Stabilized solid oxide electrolyte (Y2O3, ZrO2)	Solid polymer membrane
Operating temperature (°C)	~650	800-1000	60-200
Anode reaction	$H_2O + {CO_3}^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O_2 \rightarrow H_2O + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6H^-$
Cathode reaction	$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow {CO_3}^{2-}$	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$	$3O_2 + 12H^+ + 12H^- \rightarrow 6H_2O$
Charge carrier	CO_3^-	O^-	H^+
Fuel	H_2, CO, CH_4, other	H_2, CO, CH_4, other	CH_3OH
Efficiency	>50%	>50%	40%
Cell Voltage	0.7-1.0 V	0.8-1.0 V	0.2-04 V
Advantages	High efficiency: no metal catalyst needed	Solid electrolyte; high efficiency; generate high grade waste heat	Reduce cost due to the absence of a fuel reformer
Drawbacks	High cost; corrosive liquid electrolyte; slowly start up; intolerance to sulphur	High cost; slowly start up. Intolerance to sulphur	Lower efficiency and power density

By comparing the different technology of both electrolysers and fuel cell, we can see obviously that the SOC systems are very promising because they have the high efficiency though they are still under development. To harness this high potential, a lot of research has to be done in this area. Therefore, it is necessary to have an SOC emulator for the different kind of measurement in the Laboratory.

I.2 Basic principle of SOC system

I.2.1 Solid oxide Electrolyser

Like all types of electrolysers, SOEC is an electrochemical device that converts electrical energy to chemical energy. It consists of two electrodes that are separated by a layer of dense ion-conducting ceramic electrolyte. For steam electrolysis, water is reduced in the porous fuel electrode under an applied voltage, forming hydrogen and oxide ions (Laguna-Bercero, 2023). The oxygen ions transfer through the electrolyte and are oxidized into oxygen in the oxygen electrode, illustrated in the equations below **Figure 3** gives the schematic of SOEC.

Fuel electrode:

$$2H_2O(g) + 4e^- \rightarrow 2O^{2-} + 2H_2 \tag{I-1}$$

Oxygen electrode:

$$2O^{2-} \rightarrow 4e^- + O_2(g) \tag{I-2}$$

Overall reaction:

$$2H_2O(g) \rightarrow 2H_2(g) + O_2(g) \tag{I-3}$$

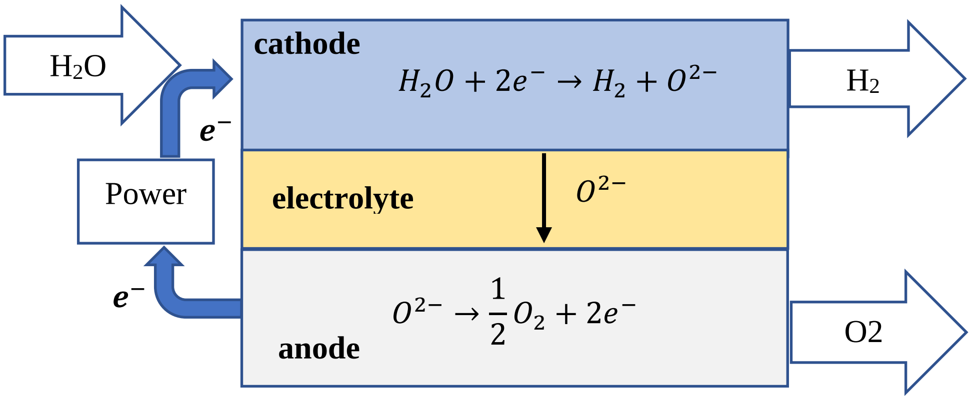

Figure 3 : Schematic representation of an SOEC for water splitting

I.2.2 Solid oxide Fuel cell

Solid oxide fuel cells (SOFCs) are the most efficient devices for conversion of chemical fuels directly into electrical power. The SOFC contains a solid oxide electrolyte made from a ceramic such as yttrianzirconia (YSZ) which acts as a conductor of oxide ions at temperatures from 600 to 1000 °C. This ceramic material allows oxygen molecules to be reduced on its porous cathode surface by electrons, thus being converted into oxygen ions, which are then transported through the ceramic electrolyte to a fuel-rich porous anode zone where the oxygen ion can react (Singhal & Kendall, 2003). The **Figure 4** shows a simplified graphic of a SOFC.

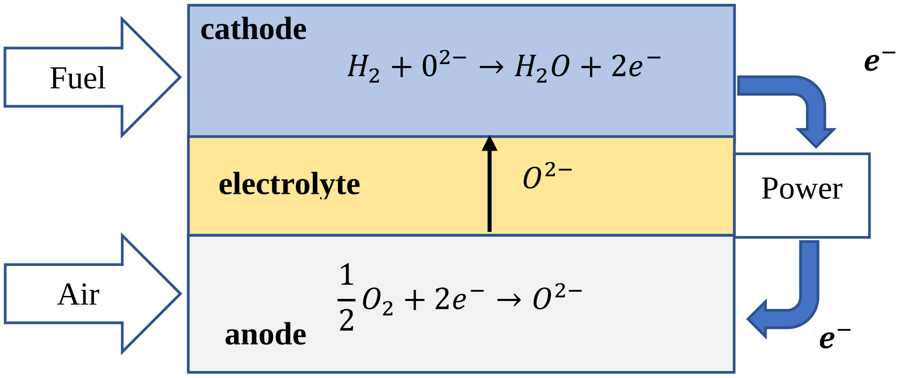

Figure 4 : Schematic representation of an SOFC

I.3 Review on Systems Emulator

Several studies have been done on emulators. A programmable solar emulator is used to test solar panels equipment or product such as characteristics of the solar cells and maximum power tracker circuit, since high power PVs are expensive and testing the power electronic for varying solar conditions is difficult(Cham Yew Thean et al., 2005) . Furthermore, some studies have been done on emulator in (Chou et al., 2003) to replace battery. According to this study we have two main reasons why battery emulator should be used instead of real batteries. First, because battery emulator is cost effective than real batteries, and for the case of rechargeable batteries we have the discharge and recharge history of the battery that will affect the total charge level each time. On the other hand, for the case of non-rechargeable batteries, they must be replaced and disposed of after each experiment, making this approach expensive and unfriendly to the environment. With the increasing demand of fuel cells and electrolysers in all sectors due to the Climate crisis, the study of these technologies emulation becomes vital.

A fuel cell emulator based on a dynamic lumped SOFC model, which accounts for the effects of activation, concentration and ohmic loss is proposed in (Gebregergis & Pillay, 2007) . This SOFC emulator is implemented in a Matlab/Simulink environment and programmed into a dSPACE and/or DSP controller. The controller generates an output control voltage, which is fed to a linear power amplifier capable of high output current, and the emulator is tested for various cell temperatures, flow rate concentrations and load changes to predict the static and dynamic response. A related study was presented on the emulation of PEMFC response by a remotely controlled DC source(Tritschler et al., 2010). According to this study the stack is replaced by a programmable DC-source providing the characteristics of the real stack through a Simulink model that controls this source via a dSPACE system. The control of the DC source is managed through a user-friendly interface running on Matlab Simulink which allows testing new algorithms dedicated to the control of the FC power interface easily and without any risk for the FC. A modular hardware-in-loop emulator for water electrolysis is presented in(Ruuskanen et al., 2016) . This emulator is used to study the behaviour of the electrolysers as a part of a smart grid with high penetration of renewable energy generation. An interesting approach is presented in Lindahl et al., (2018) , where they have developed an emulator allowing both cell and hardware in the loop stack simulations. In this technique, an amplifier takes as input the voltage of a reference fuel cell and reproduces the “scaled-up” voltage that would be provided by a stack of similar cells. One of the advantages of this emulator is the flexibility to emulate multiple fuel cell types. Alternatively, talking about flexibility, in Boscaino et al., (2010) presented another emulator that can be applied to any fuel cell types. In this method, An FPGA based controller models the fuel cell steady-state and dynamic behaviour, including temperature effects. The fuel cell model was described by a proper selection of mathematical equation which can be readily described by VHDL and implemented on an FPGA. Another FC emulator Gebregergis & Pillay, (2010), which includes both the steady-state and transient responses of an FC. For this system a Matlab/Simulink environment is used to implement the FC model, converted and compiled it into a C-program and build into a real-time control, which is finally programmed into a dSPACE and/or DSP controller for prototype testing and design and field testing. Most of the studies presented above take into account only the electrical domain, Fei Gao et al., (2011, 2012) present a multiphysical proton exchange membrane fuel cell stack model. This model is divided into three submodels describing the different physical domains, namely, electrical, fluidic, and thermal. Another system was developed in Shekhar Das et al., (2017), using MATLAB/Simulink based fuel cell model. This system consists of a buck DC-DC converter and a proportional integral (PI) based controller incorporating an electrochemical model of PEMFC used to generate reference voltage of the controller which takes the load current as a requirement. In Koubaa et al., (2011), is describe an interesting study on the emulation of both electrolyser and fuel cell photovoltaic application. These emulators are based on power electronic circuits and the reference values of the two emulators are taken from fuel cell and electrolyser mathematical models. Finally ,Yodwong et al., (2021) and

Ruuskanen et al., (2018) present two different approaches of emulating PEMEC for power electronics testing applications.

After, going through the literature, we can obviously see that most of the electrolyser and fuel cell emulator developed are model based and focused on PEM technology. In this study, the aim is to develop an SOC Hardware based emulator, and also that can be apply for any types of fuel cell or electrolyser depending on the data input to the system. Due to the time constraint, we will limit the work at the level of the voltage emulator. **Figure 5** gives the diagram of the entire emulator.

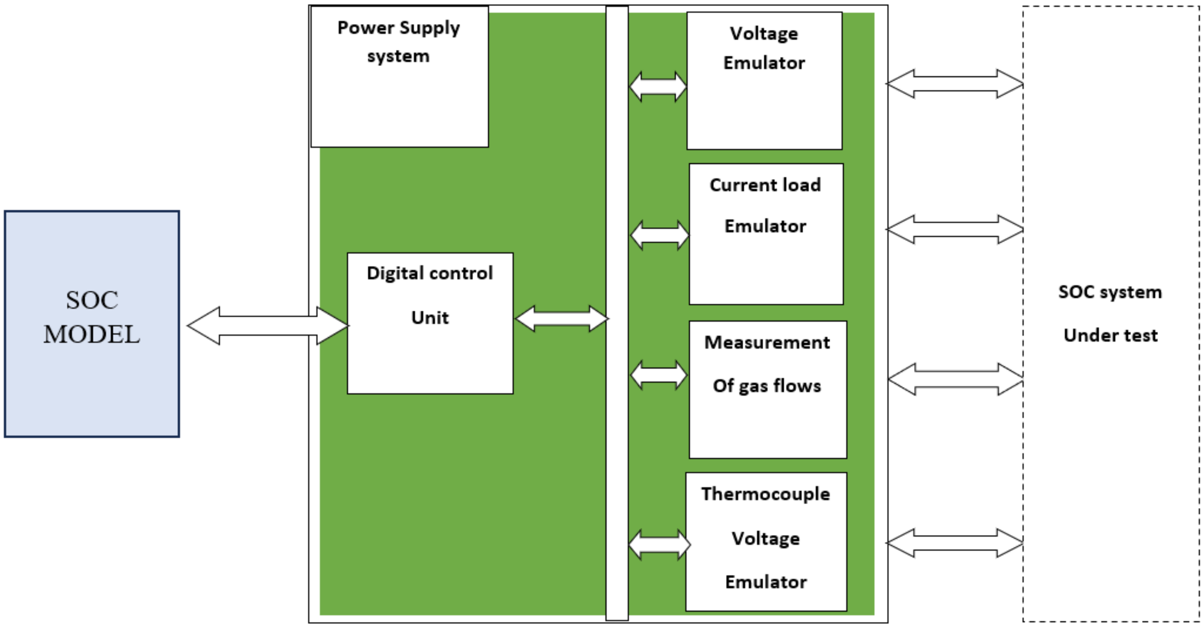

Figure 5 : SOC stack emulator

CHAPTER II.

MATERIALS AND METHODS

II.1 Methodology

The objective of this study is to design and implement a solid oxide cell (SOC) stack voltage emulator capable of accurately simulating both the static and dynamic characteristics of SOEC and SOFC. This methodology section outlines the design process and key components used in the emulator. **Figure 6** gives the flowchart of the process followed during our work and **Figure 7** the overview of the voltage emulator.

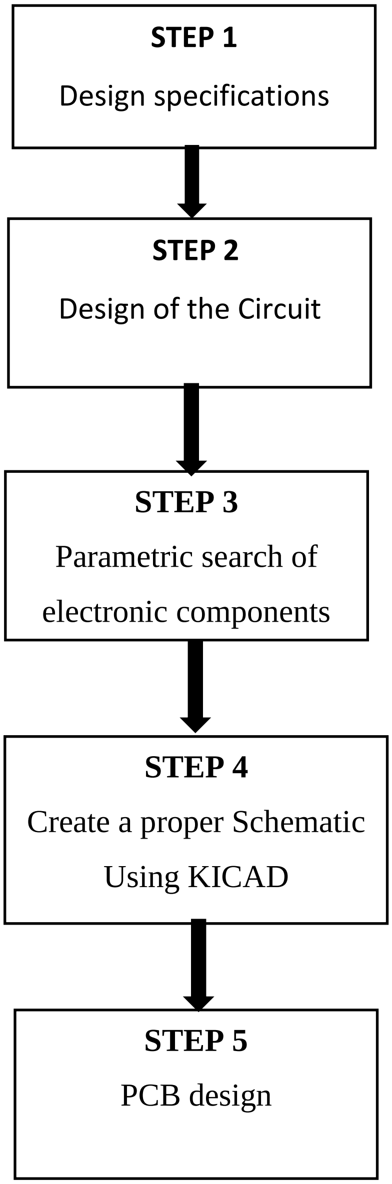

Figure 6 : Flow chart of the methodology

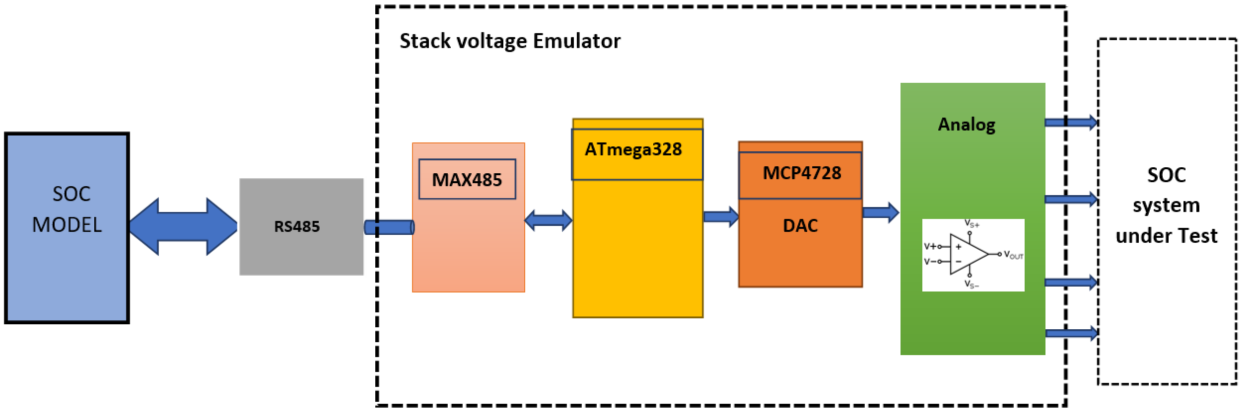

Figure 7 : Diagram of the stack voltage emulator

II.1.1 Design Specifications

To meet the stated objectives, here are some specifications of the system:

- Input Signal is a digital value from Modbus-rtu Protocole To RS-485
- Number of output voltages for one module is 4; so that we can emulate 80 cell layers with 20 cascaded modules.
- Output voltage/cell-layer: 0 to 1.5 V
- Total maximum voltage span of one module: 30 V
- The minimal output current of each output: 1 mA
- System Power Supply: 24 V
- Operating Temperature: Normal conditions (the system should be usable in a lab environment as well as outside in mobile containers with ventilation but no air conditioning~~)~~
- Each output should be current limited (inward and outward flowing current) to protect the module against short circuits between the outputs.

II.1.2 Digital part

This part of the circuit is mainly constituted of the microcontroller and communication interface. the role of this section is to:

- Generate control signals for various parts of the SOC
- Process the data and convert analogue signals to digital.
- Serve as interface with external devices or software through communication interfaces.

II.1.3 Analogue part

The analogue part of the emulator plays also an important role, because is the one adjusting the voltage and current output according to the need. It is composed of the elements like resistors, capacitors, transistors, and operational amplifiers.

The circuit below was used as main circuit for the Analogue part. Basically it is a non-inverting operational Amplifier, in order to avoid any fluctuation for the circuit some capacitors and Transistors has been added (Appendix 2)

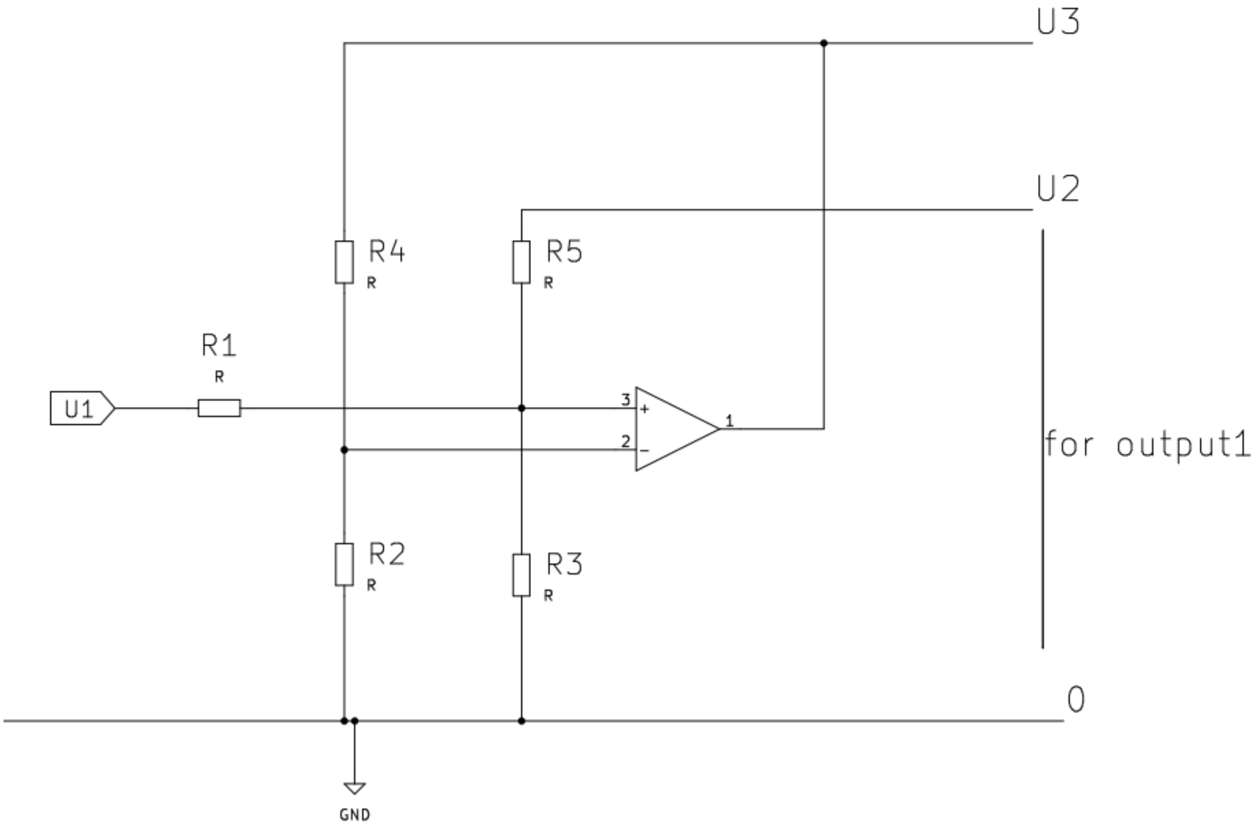

Figure 8 : Operational Amplifier configuration

In order to match the ADC output range of the cell voltage range of 0 to 1.5 V.
The max. op-amp common mode input voltage can be kept as high as possible but below the op-amp supply voltage.

Here is a python code for the calculation of the value of the different resistors used and the Cell voltage.

```
U1 = 2.048 # V (output range of DAC MCP4728)
U2 = 10     # V (sum voltage of all the emulated cells below)
target_voltage_difference = 1.5 # Desired U3 - U2

R4 = 330e3 # Ohm
R5 = R4
```

```
# Adjusting the op-amp common mode input voltage to 1/5 of the
# output voltage U3 (e.g. 100 V / 5 < 24 V)
R3 = R4 / 5

# Calculate R2 to achieve the desired voltage difference
R2 = R3 * (U2 + target_voltage_difference) / U2

# The sum of electrical conductance for R1 and R2 must match
# R3 to achieve a constant gain independent of U2
R1 = 1 / (1 / R3 - 1 / R2)

# op-amp common mode input voltage
Ucm = (U1 / R1 + 0 / R2 + U2 / R5) / (1 / R1 + 1 / R2 + 1 / R5)

U3 = Ucm / R3 * (R4 + R3)

print(f"R1: {R1 * 1e-3:0.2f} kOhm")
print(f"R2: {R2 * 1e-3:0.2f} kOhm")
print(f"R3: {R3 * 1e-3:0.2f} kOhm")
print(f"R4, R5: {R4 * 1e-3:0.2f} kOhm")
print(f"U3: {U3:0.4f} V")
print(f"U3-U2: {(U3 - U2):0.4f} V")
print(f"Ucm: {Ucm:0.4f} V")
```

II.2 Materials and Tools

For the implementation of the voltage emulator, we have chosen KiCad as software for the design and test for some reason that we will present later. We decided to use the SMD technology for most of the components as we are going to design the circuit on multilayer PCBs.

Like for all electronic circuits, we must provide a power supply. For that, we have used the LM340 linear regulator after evaluation of the power dissipation of the component. Then comes the microcontroller atmega328 and the Module for the communication Max485E, connected to the computer via RTS485. Four-module DAC(MCP47280) for the conversion to analogue signal.

On the Analog side of the Circuit, we used the following components: operational amplifiers, Transistors, resistors, and some Capacitors according to the need.

II.2.1 Presentation of KiCad

In the development of the SOC stack voltage emulation, the choice of an appropriate Electronic Design Automation (EDA) tool was crucial to ensure an efficient and accurate design process. After careful evaluation of available options, KiCad was chosen as the preferred software suite for our electronic design and layout due to its outstanding features and extensive capabilities.

First, one of the primary reasons for choosing KiCad was its open-source nature. Being an open-source EDA tool, KiCad provided a cost-effective solution that aligned well with the project's budget constraints. Moreover, its open-source nature allows continuous community-driven development, ensuring that KiCad is constantly evolving, improving, and staying up-to-date with the last advancements in electronic design.

Second, Kicad comprehensive suite of tools was another key factor in its selection. It offers a range of essential functionalities, including a Schematic Editor for intuitive circuit creation and editing, a PCB Layout tool for designing the physical layout of the circuit, and a 3D Viewer to visualize the assembled PCB in a realistic 3D environment. These tools collectively facilitated a seamless design flow, from capturing the circuit schematics to optimizing the physical layout for enhanced performance.

Third, KiCad offers a powerful Design Rule Check (DRC) and Electrical Rule Check (ERC)capabilities provided essential validation and verification mechanisms. The DRC ensured that the PCB layout adhered to manufacturing constraints, while the ERC helped detect and resolve electrical errors and inconsistencies in the schematic. These features significantly reduced the errors and enable a more reliable design process.

Finally, KiCad has a vibrant and supportive community that is playing a vital role in the selection process. Active community forums like "KiCad Forum" provide valuable support, insights, and learning opportunities. The collaborative environment allowed for interactions with fellow engineers and hobbyist, fostering knowledge exchange and project ideation.

II.2.2 Spice simulation

KiCad integrates the open-source SPICE (Simulation Program with Integrated Circuit Emphasis) simulation ngspice to provide simulation capability in graphical form through integration with the Schematic Editor. SPICE simulation is a powerful technique that allows engineers and researchers to model and simulate complex electronic circuits, providing valuable insights into their behaviour and performance. By employing SPICE, I was able to virtually test and validate various components and circuits, including operational amplifiers, DACS, voltage regulators, before physical implementation. This pre-emptive approach proved immensely beneficial, as it significantly reduced design iterations, cost, and time spent on prototype development. SPICE simulation enabled me to explore different scenarios, evaluate the effects of parameters variations, and uncover potential issues such as signal distortions, noise, and stability problems. Furthermore, SPICE facilitated the study of dynamic response and transient behaviours, offering a deeper understanding of my system’s characteristic under various operating conditions. Overall, the use of SPICE simulation played a pivotal role in enhancing the efficiency and accuracy of my work, ultimately contributing to the successful realization of the Solid oxide voltage emulator.

II.2.3 Power Supply

For the choice of the power supply, we evaluated the power consumption of all the devices and calculated the power dissipation of the regulator by using the equation below. After we search for a suitable regulator meeting the required power. We decide to go for the LM340, with 35V as Maximum input voltage, 5V output voltage and can deliver over 1.5 A if adequate heat sinking is provided. The schematic below shows the regulation part of the emulator. The input capacitor is used to avoid oscillation of the input voltage if the regulator is far from the power supply and the output voltage is used to improve transient response.

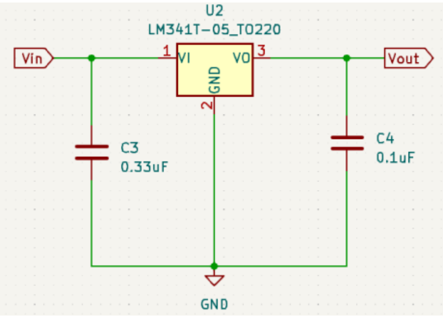

Figure 9 : Circuit of the LM340

$$P_{diss} = (V_{in} - V_{out}) * \sum I_d \qquad \text{II-1}$$

With P_{diss} the power dissipated by the regulator, $\boldsymbol{V_{in}}$ is the voltage at the input of the regulator, $\boldsymbol{V_{out}}$ is the voltage the output of the regulator and I_d is the current draw the component supplied by the regulator.

Here are some calculations for the choice of the linear regulator:

I search for the current draw by all my devices on the rail 5V (ATmega ; Max485E; MCP4728)

Atmega : I found the value of 9.8 mA Active mode in the datasheet

Max485E: I found the range of 120uA to 500uA , so I took I =500uA

MCP4728 (5*4 outputs)-DAC : 800uA (For the current design we need only on DAC)

Looking at the specification of the regulator, we have:

Vout = 5V; Vin = 24V

The power dissipation will be given by the formula: $P = (V_{in} - V_{out}) * I$ with $I = \sum I$=9.8+ 0.5+0.8= 11.1mA=0.011A

P= (24-5) * 0.011= 0.209W

II.2.4 Microcontroller:

For good monitoring of the system and for good communication, the microcontroller used is Atmega328P. It is a popular microcontroller due to it being a major component in Arduino board products. The choice of Atmega over Arduino board is because of its flexibility, low price, and we can directly integrate it into the PCB. For operating like a real Arduino board, we need to connect some external components. The basic circuit is composed of a 16 MHz crystal, two 22 pf Capacitors for the Crystal, and one resistor for the reset.

The table below summarizes some key characteristics of the ATMEGA328PB (*Empowering Innovation | Microchip Technology*, n.d.).

Table 4 : Specifications of ATmega 328PB (two USART)

FEATURES	ATMEGA328PB
PIN COUNT	32
FLASH (KB)	32
SRAM(KB)	2
EEPROM	1
GENERAL PURPOSE I/O PINS	27
SPI	2
TWI (I^2C)	2
USART	2
ADC CHANNELS	8
8 BITS TIMER/COUNTERS	2
16 BITS TIMER/COUNTERS	3
PMW CHANNELS	10

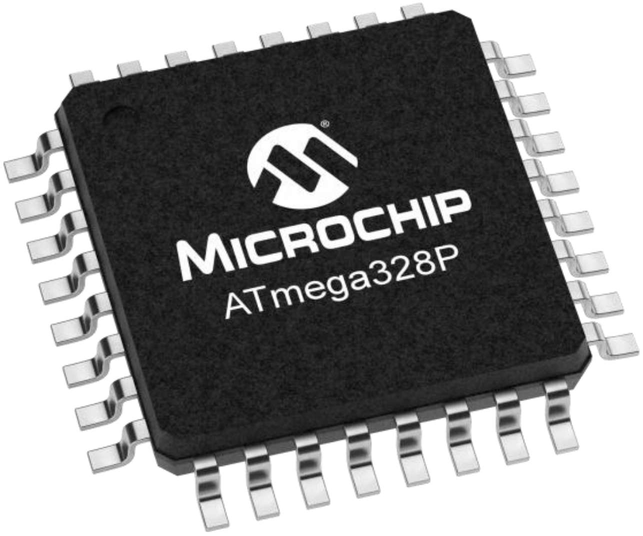

Figure 10 : ATmega328P Microcontroller (DigiKey)

II.2.5 Digital to Analog Converter

A Digital to analog converter takes the digital value from the ATmega and outputs an analogue voltage. Considering the number of outputs we need, MCP4728 is the suitable components for our application. For connecting the MCP4728 first we use two 10K resistors connected on pins 4 and 5, the SDA and SCL pins respectively. The resistors pull the pins to the VDD potential (they are called pull-up resistors). The I^2C interface needs them for proper operation. Third, a 1.0 microfarad capacitor connects the VDD and GND pins. This is a power supply de-coupling capacitor. Its primary use is to prevent voltage fluctuation due to the DACs changing current demand. And lastly, the screw terminals break out all the MCP4728 pins for external connections. The schematic below shows the Circuit allowing the conversion from one input digital to 4 outputs analog.

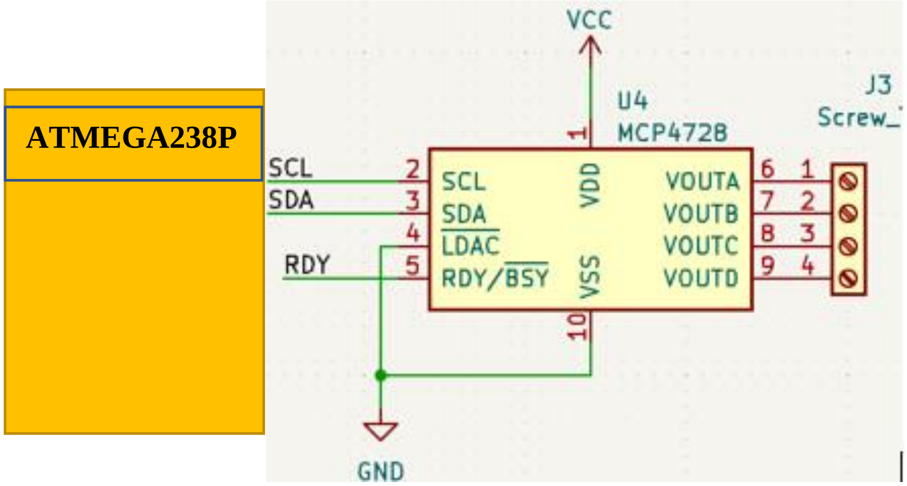

Figure 11 : Schematic diagram of the MCP4728

II.2.6 RS285 interface

For communicating with our System, we will use Modbus protocol because of the multiples advantages it gives. The RS-485 standard allows for long cabling distances in electrically noisy environments and can support multiple devices on the same bus. For establishing the RS285 interface, MAX485E is needed for converting the voltage level between PC and Microcontroller.

The RXD pin of the ATmega328P is connected to the RO pin of MAX485 RS485 chip, so data received from the RS485 line is sent to the receive pin of the Microcontroller. TXD pin of the ATmega328 is connected to the DI pin of MAX485, so whatever data is transmitted by ATmega328p is sent to the MAX485 chip and out to the RS485 twisted pair cable. PD2 is connected to RE pin of MAX485 which is Active low. Making this pin low would put the MAX485 in Receive mode. PD3 is connected to DE pin of MAX485 which is Active High. Making this pin High would put the MAX485 in Transmit mode. The **Figure 12** shows the interconnection.

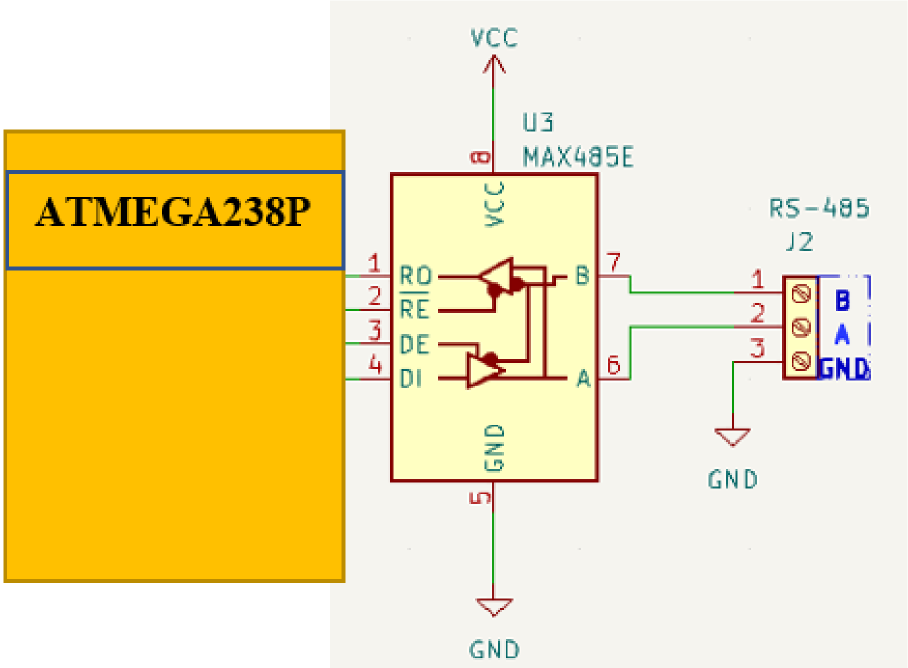

Figure 12 Schematic diagram of The RS485 interface

II.2.7 Programming interface

This is the most important things to handle if we want to use any microcontroller. For the case of the ATmega328PB, we will use the port ISP of the microcontroller. The hardwire needed are:

- AVR ISP MK2
- 6 PINS HEADER

The **Figure 13** gives a view of the interconnection with the microcontroller.

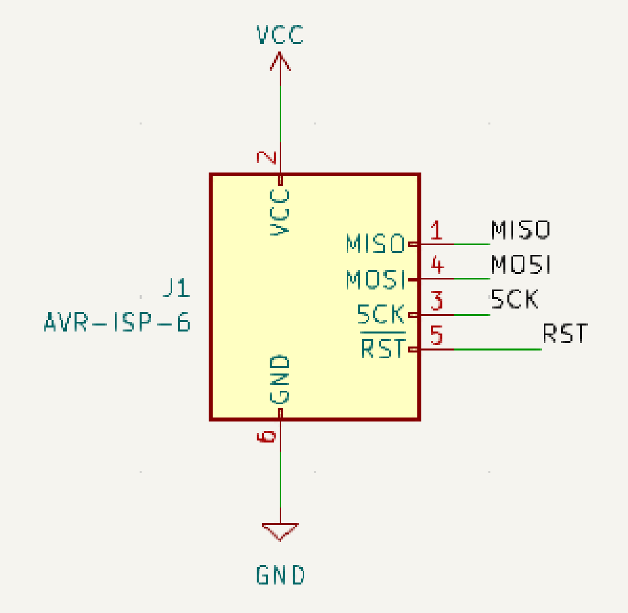

Figure 13 AVR-ISP MK2

CHAPTER III.

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

III.1 Simulation results and performance analysis

In this chapter we present the results of the simulation experiment conducted to analyse the transient response and stability of the analogue output stage in response to a step function input. The objective of this simulation is to test the analogue part of our circuit being the most complex, in order to see its performance and suitability for the stack voltage project.

The analogue output circuit use in the simulation, is composed of four identical cascaded circuits, each responsible of emulating the voltage output of SOC cell. The simulation was performed using the KiCad software with ngspice as the underling simulator. A time duration of 80ms was chosen for the simulation, with a time step of 1us. **Table 5** present the characteristics of the step function.

Table 5 : Characteristics of the Step function

Input Signal (Step function)		
Parameter	Value	Unit
Initial value	0.5	V
Pulse Value or amplitude	2	V
Delay	10	ms
Rise time	10	ms
Fall time	10	ms
Pulse width	10	ms
Period	100	ms

III.1.1 Determination of the voltage gain and linearity

I simulated the outputs for different amplitudes of a step input and recorded the simulation results in order to compare the voltage gain to verify the linearity of the circuit. **Table 6** and **Table 7** summaries the different value of the voltage gain for output 1 and output 2 respectively. The equation III-1 is used to calculate the voltage gain.

$$\boldsymbol{V}_G = \frac{V_{out}}{V_{in}} \qquad \text{III-1}$$

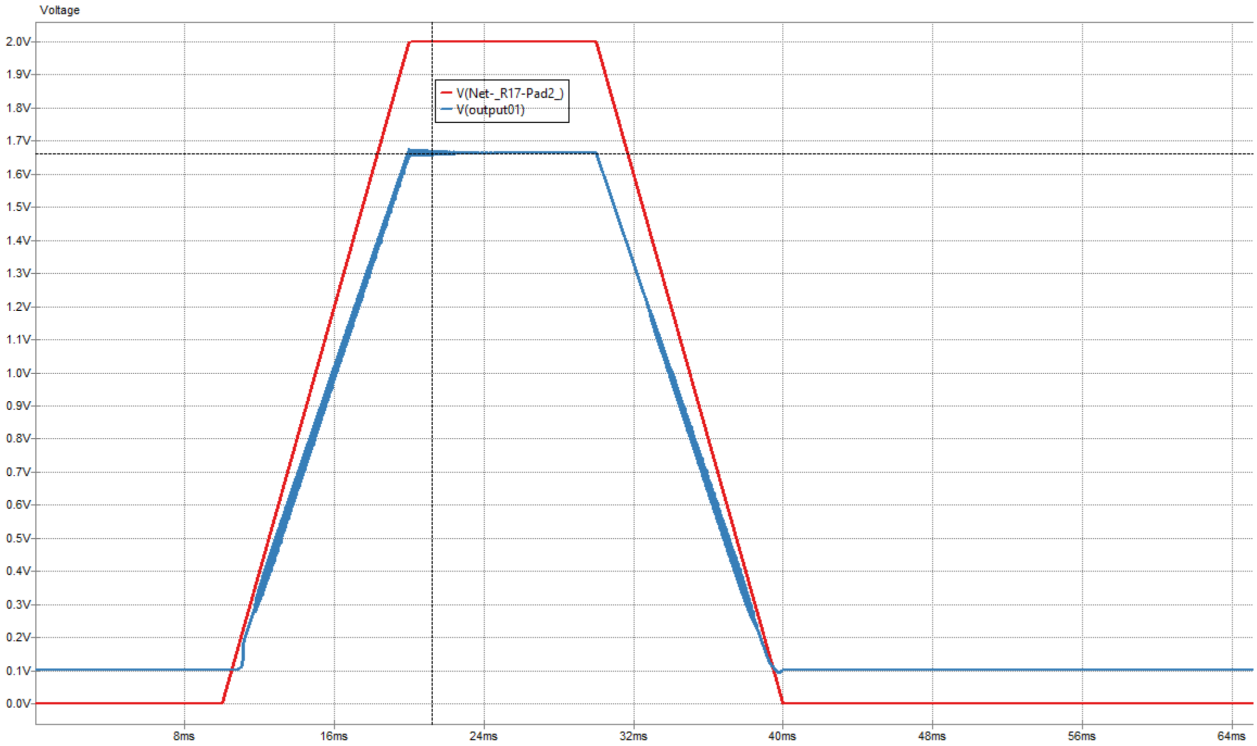

Figure 14 : Output 1 vs input step

Table 6 : Voltage gain of the output 1 at different Amplitude of step voltage

INPUT VOLTAGE(V)	OUTPUT 1 VOLTAGE(V)	VOLTAGE GAIN (VG)
2	1.66	0.83
3	2.49	0.83
4	3.35	0.83

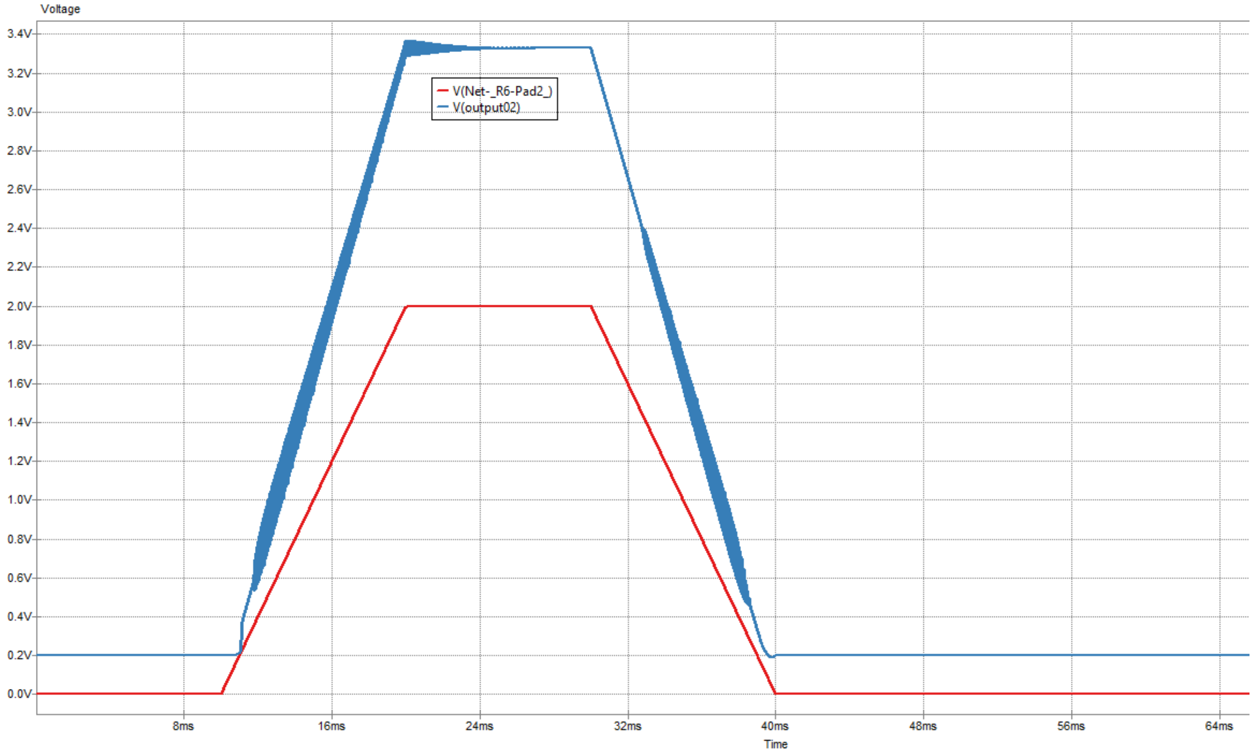

Figure 15 : Output 2 V vs input step

Table 7 : Voltage gain of the output 2 at different Amplitude of step voltage

Input voltage (V)	**Output 2 voltage (V)**	**Voltage gain (VG)**
2	3.32-1.66 = 1.66	0.83
3	4.994- 2.49 = 2.5	0.83
4	6.66 - 3.33 = 3.33	0.83

The observed voltage gain of 0.83 for the outputs indicates the amplification capacity of our circuit. This value suggests that for every unit increase in the input voltage, the output voltage increase by 0.83 units. The consistent gain across all the outputs voltage means that the circuit ability to provide a reliable and proportional amplification effect. From this information we can conclude that the circuit accurately scaled the input voltage, reflecting the desired linear response.

III.1.2 Transient time response

For testing the performance of our system, the transient time response is very crucial because it give an idea of how fast the system respond to the change in the input. To achieve this, we are going to determine the rise time and the settling time of the output stage. Equation gives the formular of the Rise time.

III.1.2.1 Rise time

$$Rise\ time = t_2 - t_1 \qquad \text{III-2}$$

With t_1 the time at 10% of the finale value of the output and t_2 the time at 90% of the final value.

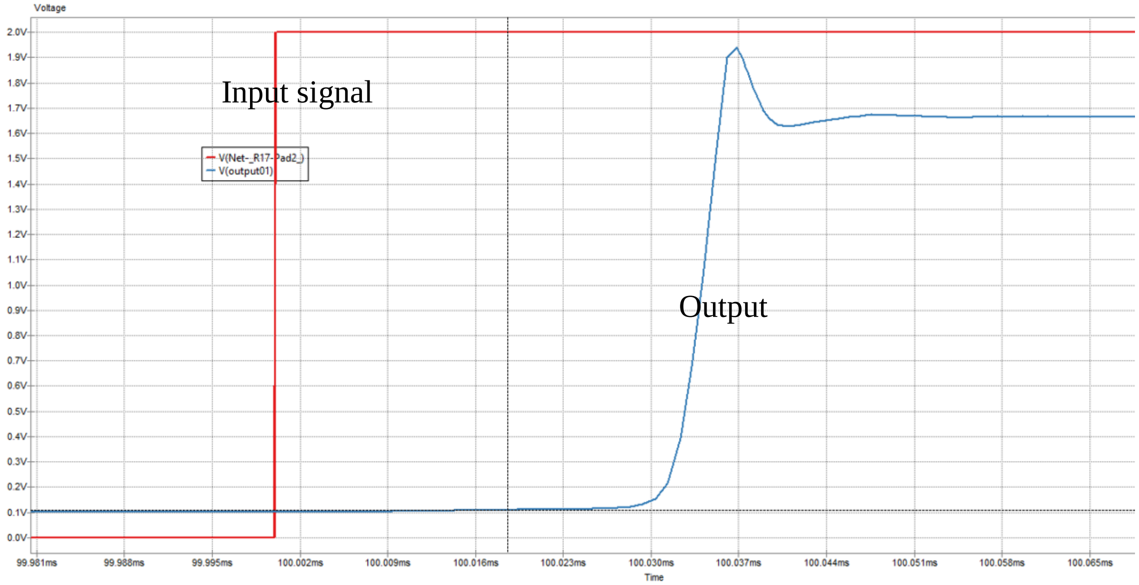

Figure 16 : Output1 vs Input step

From the **Figure 16** we can read: $V_{initial}$ = 0.1V and V_{final} = 1.66 V.

We can also read the time:

At 10% V1= 0.16 V; t1=100.03 ms

At 90% of V2= 1.494 V; t2= 100.035 ms

$$\boldsymbol{Rise\ time} = t_2 - t_1 = 100.035 - 100.03 = 5\ us$$

The rise time of 5 microsecond indicate how quickly our circuit responds to changes in the input signal.

This value signifies the time it takes for the output voltage to transition from 10% of its initial value to 90% of its final value after a step input is applied. I t also suggest that our system achieves a relatively moderate responds speed to sudden changes, with the output voltage reaching its new level within this time frame. This information provides insight into the dynamic behaviour of our circuit.

III.1.2.2 Settling time

The settling time is a key parameter that characterise the time it takes for a digital signal to stabilise and remain within a certain range around the final value after a step change in the input signal. It measures the duration required for the system to settle to a steady state after experiencing a transient response.

Taking a marge of 5% of the final value Vf = 1.66 V

- Lower Voltage Limit = 1.66 V - (0.05 * 1.66 V) = 1.66 V - 0.083 V = 1.577 V
- Upper Voltage Limit = 1.66 V + (0.05 * 1.66 V) = 1.66 V + 0.083 V = 1.743 V

T1 = 99.99 ms ; T2 =100.058 ms

Settling time = T2-T1 = 68 us

The achieved settling time of 68 microseconds represents a noteworthy aspect of our system's performance. This relatively short settling time reflects the system's capacity to swiftly stabilize after undergoing a transient response to changes in the input signal. With a settling time of 68 microseconds, our system demonstrates efficient control over transient behaviours, ensuring that deviations from the initial response are swiftly suppressed.

Conclusion and recommendation

Conclusion

With an increasing demand for alternative renewable energy sources, the need for applicable SOC cell emulators at a lower cost and great performance is vital. An inexpensive, fast, and simple emulator is important for testing purposes and other related applications. The objective of this study was to develop a reliable emulation technique for accurately replicating the behaviour of SOC stack voltages. The obtained results shed light on the system's performance, stability, and response characteristics, contributing to a deeper understanding of its behaviour.

The method employed involved the design and simulation of a multi-stage circuit that emulates the voltage behaviour of the SOC stack. The digital and analogue components were carefully selected and integrated to mirror the stack voltage characteristics, ensuring precision and fidelity in the emulation process. Extensive simulations were conducted, and the outcomes provided valuable insight into the emulator's response to varying input signals. The analysis of voltage gain, linearity, rise time, and settling time yielded crucial information about the system's performance.

The observed voltage gain of 0.83 across all outputs underscored the uniformity of application, which is a significant achievement in maintaining consistent performance. Moreover, the system's rapid rise time of 5 microseconds and settling time of 68 microseconds exemplify its swift response to changes and its efficiency in stabilizing after transients. These impressive response times further enhance the emulator's capabilities for applications requiring dynamic yet stable voltage emulation.

In conclusion, the insight gained from this research contributes to the broader advancement of SOC technology. This study opens the doors for further research on the SOC emulator at large, including the refinement of emulations techniques for even higher accuracy and exploration of real-world validation through prototyping of this device. As mentioned before, the voltage emulator is one step in many for achieving the entire emulator of a SOC stack. Because of the time constraint we decided to focus on the former. To finish I would say the knowledge gained from this research has implications not only in the field of fuel cell and electrolyser but also in the broader realm of electronics and energy conversion systems.

Recommendations

Due to time constraints, a complete implementation of the Solid Oxide Cell (SOC) stack emulator was not feasible within the scope of this study. Consequently, we opted to divide the emulator into distinct sub-emulators, each addressing specific aspects of the emulation process. To achieve a comprehensive voltage emulator, the procurement of the stated electronic components and the fabrication of the PCB are imperative steps. As previously highlighted, the SOC system is inherently intricate, necessitating meticulous consideration of the electrical, fluidic, and thermal domains in the model development.

In the pursuit of a comprehensive emulation, several specific tasks are outlined for future work. Following the completion of the voltage emulator, a subsequent phase involves the development of a thermocouple voltage emulator to enable precise temperature control within the system. Additionally, a gas flow emulator is essential to accurately replicate the fluidic behaviour of the cell. Furthermore, the emulation of an electrical power source and sink is pivotal for capturing the dynamic electrical characteristics of the SOC.

These proposed future tasks are pivotal to achieving a holistic emulation of the SOC stack, enabling a more accurate representation of its intricate and interdependent domains.

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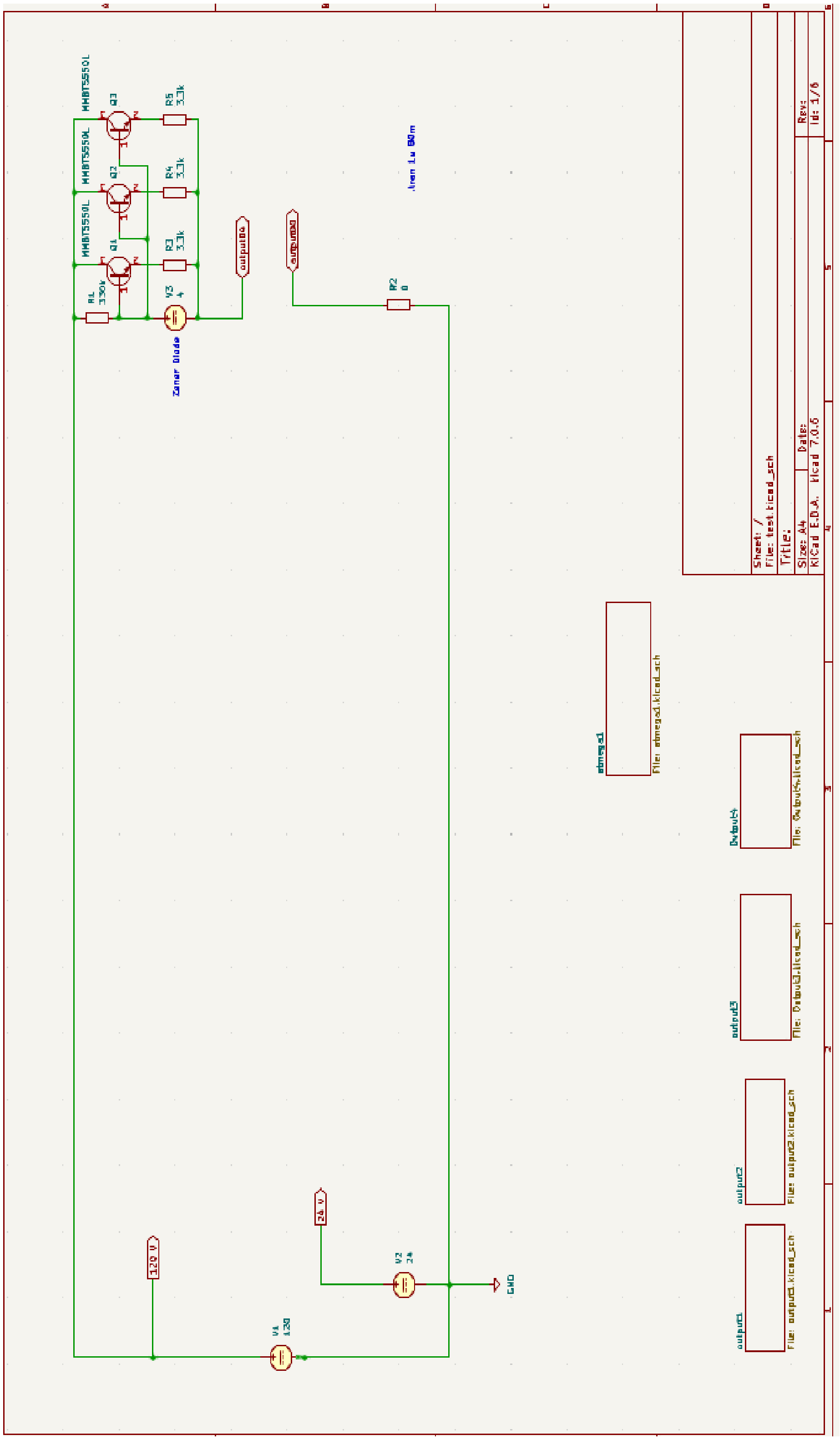
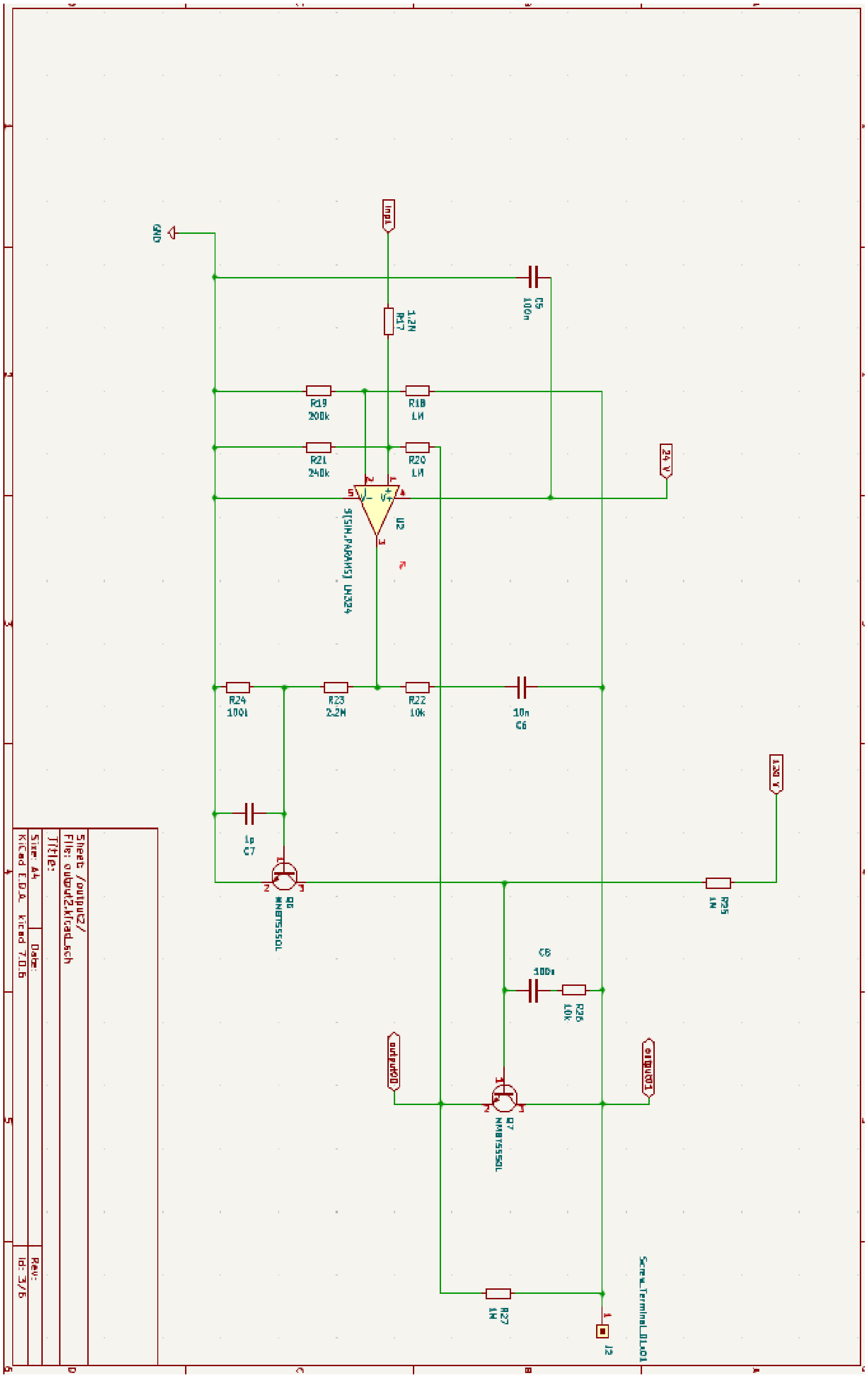
Appendices

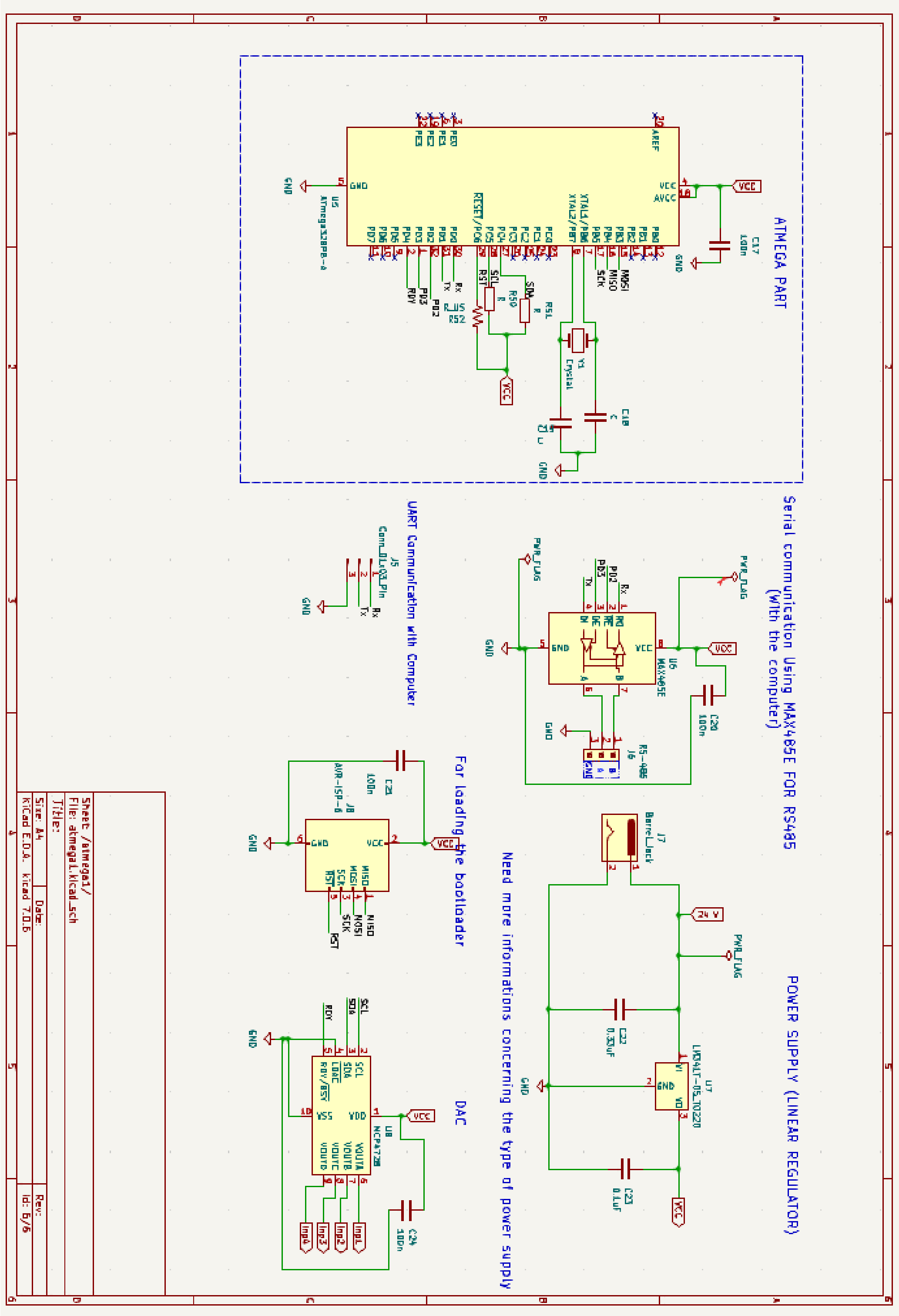
Appendix 1 Analog and digital circuit



Appendix 2 single cell circuit



Appendix 3 Digital circuit



Appendix 4 SOC stack voltage emulator