Energy Harvesting from Salty Water

by

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CERTIFICATION OF APPROVAL

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Electrical & Electronics Engineering Programme

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Approved By,

_____

(Khairul Nisak Md Hasan)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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BILAL MUHTHASSIM

ABSTRACT

Energy harvesting from salt water is a phenomenon that began in the 1970's and should have reached its peak by today, but due to varying interests in the field and the growing potentials of other more promising sources, more work was required to fully establish it. Our research aims at identifying and comparing the existing techniques of energy harvesting and the methodology involved determining an effective technique for small scale applications of the method. Experimentation on the proposed technique involved electrolysis and determining the output at varying concentrations of solutions and was followed by circuit analysis for DC-DC boost applications designed in MATLAB for low power circuit applications, involving stepping up the input voltage to 5V for system enhancement.

Small scale applications of energy harvesting needs more in depth study, and future work will be to develop a mechanism for providing more regulated power.

ACKNOWLEDGEMENT

First and foremost, all praise to Allah the Almighty for his blessings and guidance. My heartfelt gratitude goes out to my project supervisor Pn. Khairul Nisak Md Hasan, who has been my supervisor for more than a year now, from internship until my final semester and for teaching me to have high standards and not to be satisfied with less than the best and for giving me the chance to work with her. I would like to thank her for the constant guide and support throughout. I would also like to thank all of those who helped and made sure the project was a success and the valuable experiences I learned from it.

Last but not least I would like to thank my family and friends for standing beside me and supporting me until the end of the project. Their contribution, though not technical in nature, had a more profound effect than expected. Simply thanking them for all that they have done does not do enough justice, but all I can say is, Thank you. It has been a wonderful journey and I would not be in the position that I am now if not for unwavering support from everyone involved.

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CHAPTER 1
INTRODUCTION

Water is the most abundant resource in existence on Earth. 71% of the Earth's surface is covered in water, with the ocean holding 96.5% of all the Earth's water. With all the interest in renewable sources of energy being derived from the sun and wind, the extraction of energy of water never fully reached its full potential.

A major method of harvesting the energy in water is by tapping in to the salinity differences of freshwater and salty water. The energy produced from mixing these two solvents produces significant electricity, with its effectiveness being determined mainly on the potential gradients.

Research on harvesting electricity using the concentration differences of freshwater and sea water has led to the coining of the term "Blue Energy" [1] to refer to the energy/power that is produced from harvesting sea water. The interest in energy harvesting reached a peak during the late 70's as well as in recent times, corresponding on both instances, with lowered oil feed supply and security. [2]

Large scale electricity production from salt water has been underway in recent times with a 50kW test power station unveiled in late 2014 on the Afsluitdijk, an embankment on the coast of the Netherlands, in addition to the plant being fully functional and providing nearly 10% of the electricity needed in the country, it is also a research centre for further improving the methods of energy harvesting from the salinity differences between fresh and salt water [1]

Another significant research was carried by researchers at Massachusetts Institute of Technology (MIT) to develop a model to optimize the Pressure Retarded Osmosis system – the most common process for energy harvesting.[3]

1.1 Problem Statement

In recent times, with the relative instability of oil prices and non-renewable energy sources, and their resources plunging, the interest of harvesting energy and electricity out of renewable sources of energy has spiked. [4]

- Energy/Electricity produced from renewable energy sources have always fallen short in comparison to energy produced from non-renewable sources. This issue needs to be addressed if renewable energy (and more particularly Blue Energy) is to be deemed desirable to consumers as well as developers.
- In disaster affected areas (floods, earthquake), there is little being done to ensure electricity generation. A portable extraction mechanism for producing electricity needs to be researched, and a prototype development of harvesting energy from salty water should be looked into.
- There has been a recent spike in interest in energy harvesting from salty water for its potential. Due to lack of information, and immature technology available, extensive research in the area needs attention. There is almost non-existent work done in Malaysia except for the theoretical investigation of energy conversion from salinity gradients.

Regarding these issues, this paper aims to review the implementation of the process of electricity production from salty water as well as to identify the possible implementation in Malaysia by reviewing the relevant researches in energy harvesting techniques. Based on these techniques, we aim to find sustainable alternative solutions for energy production from salty water with the most efficiency.

1.2 Objectives and Scope of Work

The overarching aims of this project will aim to achieve the following:

- To review the state-of-the-art energy harvesting techniques from salty water and provide a critical analysis literature
- To analyse and experiment the techniques of electricity production from salt water, on a small scale and compare to more mature techniques such as PRO and RED for analysis.
- Analysis of experiment and then further the study in order to construct a working prototype through the extracting of electricity from the salinity difference that can be used in rural areas where electricity is difficult to come by.

CHAPTER 2

LITERATURE REVIEW

Since the inception of the concept of desalination (removing salt from sea water for drinking and other purposes), and through the process of Osmosis, it was identified that the potential gradient between the fresh and salt water, and more specifically the salt concentrations in two solvents, released a significant amount of energy.

2.1 Pressure Retarded Osmosis

One such method of energy harvesting from salty water is the process of Pressure Retarded Osmosis (PRO) which is best suited for a situation where river water meets the sea. According to [5, 6], PRO utilizes a semi permeable membrane which separates the river water (fresh water) from the sea water (salty water). Osmosis - a process by which molecules of a solvent tend to pass through a semipermeable membrane from a less concentrated solution into a more concentrated one, thus equalizing the concentrations on each side of the membrane is the basis behind this.

Studies involving PRO stresses on the capture of energy that is released during the Osmosis process. When a static pressure is applied to the more concentrated solution i.e. – salty water, the water transported will be partially retarded. Movement of solvents from the low pressure and diluted solution toward the high pressured more concentrated solution results in an increase in overall vessel pressure. This particular amount of water can be used to generate electricity, more often through a turbine. The study carried out by

[4] on the evaluation of pressure retarded osmosis showcases a concept of the PRO system whereby electricity is generated through a turbine.

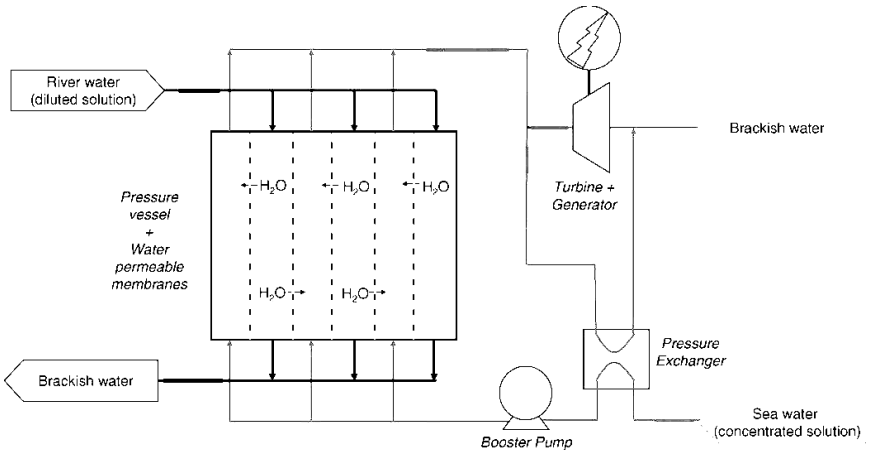

Figure 1: Conceptual demonstration of how the PRO method converts it to energy through turbine [4]

In PRO there is not much large scale data related to how much electricity can be produced, but based on the research carried out by [4], it was shown that a power density between 0.11 – 1.22 W/m^2 was obtained. The amount of energy produced depends on both the concentration of the solutions as well as the membranes used. Where [7] states that cellulose acetate membranes yield more favourable results in pressure retarded osmosis, with results of up to 2-5 W/m^2 being obtained.

The equation developed by Van't Hoff for osmotic potential difference, is expressed by the activity of the salt in the two varying solutions [2]

$$\Delta\pi = RT(a_c - a_d) \qquad \text{[Eq. 1]}$$

Where: $\Delta\pi$ = Osmotic Potential Difference

R = Molar Gas Constant (8.314 m^2 kg s^{-2} K^{-1} mol^{-1})

T = Temperature (^{o}c)

a_c = Activity of the salt in concentrated solution

a_d = Activity of the salt in diluted solution

The one limiting factor of the pressure retarded osmosis process is that generally, the larger the membrane size or amount of membranes used translates to a greater rate of PRO thus yielding more electricity, although studies as mentioned earlier by [3] aim to develop the optimal dimensions of large PRO systems to achieve maximum energy output, thus hoping to reduce cost of the energy produced, which until now, remains largely expensive.[8]

2.2 Reverse Electrodialysis

The second most popular method of energy harvesting from salty water is through reverse electrodialysis. According to [9], reverse electrodialysis or RED is the method of obtaining energy through chemical potential difference between concentrated (salty) and dilute solutions. The process is achieved through the flow of these solutions through porous electrodes.

Based on research that [10] carried out, it was identified that reverse electrodialysis is considerably expensive. However to ensure that it at least performs at its peak, is to make sure in the design that the internal resistance of the electrode cells used is minimized and average output power is maximized in order to fully achieve the desired results. This is done through incorporation of large differences in concentration gradients in order for the osmotic potential gradient to be sufficient for viable electricity generation.

In the concept describing the RED process, Sodium (Na +) ions and Chlorine (Cl -) ions are placed in a compartment. The resulting chemical potential makes the ions transport through the membranes. For sodium ions, they move through the cation membrane toward the cathode and the chlorine ions move through the anion membrane toward the anode. The spontaneous process of ionic current is converted to electricity through red-ox reactions

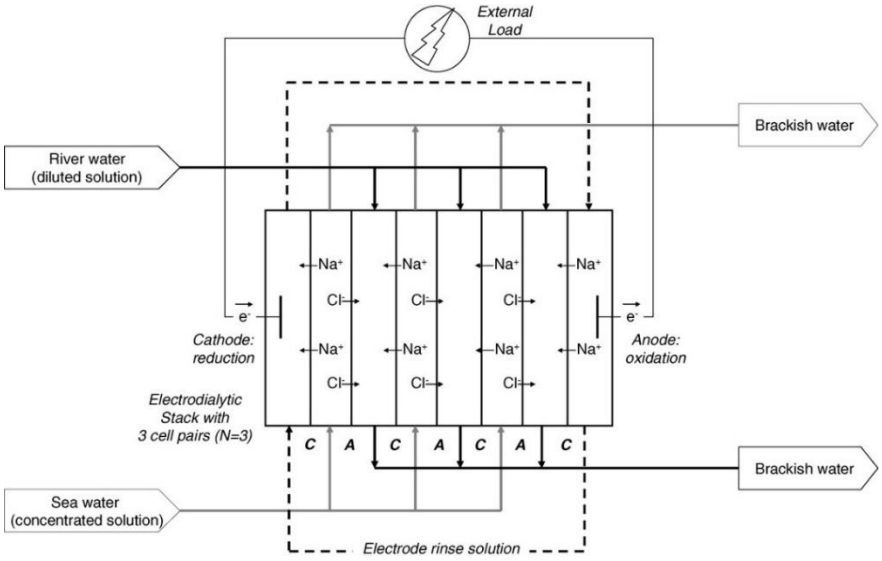

Figure 2: Conceptual demonstration of the energy conversion process using reverse electrodialysis [4]

A is classified as an anion exchange membrane, while ***C*** is a cation exchange membrane. Electro-neutrality has to be maintained throughout the process in order for electrons to be transferred from the anode to cathode and vice versa via the external circuit. This current through the electrodes is used for generation of electricity, when an external load is connected.

Based on the experimental data, in a typical scenario of freshwater and sea water mixing, the RED process yields a power density of 0.41 W/m^2 , while in more concentrated mixtures, such as brine and concentrated fresh water, a power density of 1.2 W/m^2 is achieved.

Further research was initiated by [9] on the cost of energy produced for an industrial unit running RED, with an estimate cost share of $6.79/kWh which is considerably high.

2.3 Capacitive Deionization

Capacitive Deionisation or (CDI) is the newest method of energy production from water desalination using porous carbon electrodes. According to [11], the salt ions (NaCl) are removed from salty or brackish water when it is passed through porous carbon electrodes, where these ions are temporarily stored in the electrodes, thus causing them to be charged.

Once this is done, the solution in the cell is altered by fresh water in an open circuit. This enables the stored charge to remain constant, and since the concentration of the solution has changed, it causes a greater amount of voltage to be stored. The surplus charge stored can then be tapped by discharging the cell.

2.3.1 Process

To describe further of how the process functions, two "super-capacitor" electrodes are connected and then placed in salt water. The difference in concentration gradients cause the electrodes to charge. Each electrode is also connected to a pole of an external capacitor in the circuit. This capacitor should operate at a low overvoltage and its capacity should be considerably greater than the capacity of the flow cell.[12]

During operation, while the external capacitor gains charge of the flow cell during flow of salty water in the solution (ocean), the external capacitor will gain charge again as fresh water flows through the cell making the current direction switch (opposite). The processes of events that take place in the flow cell that affect the electrodes shall be discussed.

Once in contact with salt water (more concentrate), it causes the electrons to move through the circuit (external) causing one electrode to be positive and the other, negative. At the same time, within the porous electrodes, the electrostatic double layer develops where the electrodes in the layer itself hold charge. Formation of this layer continues to vary when it is placed back in fresh water which causes it to expand (V_{cell} initially small becomes equal to V_0) thus resulting in an increase in cell potential V_{cell} more than V_0 causing the flow of electrons to reverse, re-charging the external capacitor.

What must be noted is that the system is placed in water that is continuously flowing, which is ideal in the context of sea water, though it is also possible to place the system in stagnant water, although expect the power output to be low.

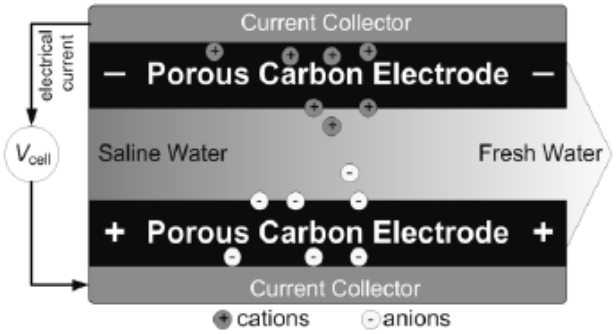

Figure 3: General outline of the arrangement of electrodes and how the capacitive charge is extracted [6]

As described earlier (in salt water), the constant flow based on the structure, causes V_{cell} to be equal to V_o. Once done, it is then placed in fresh water, which will cause the layer to expand.

Throughout the experiments conducted, [6] achieved V_o of between 0.3V – 0.7V, as the variation in charge stored depended on the salinity gradients. This was where carbon electrodes were used and in a fixed salinity concentration of 500mM. If the initial solution had exceeding salinity and was then placed in fresh water or if the system was considerably larger (industrial scale) it would yield much higher voltages. What is interesting to note is that one form of capacitive deionisation does not incorporate membranes unlike the other two techniques.

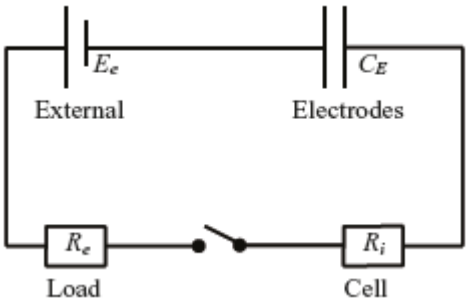

Figure 4: Circuit analogy of Figure 3 which uses the capacitive double layer expansion

Based on the methods described above, the capacitive deionization method, though more recent, is suitable for experimentation for proof of concept of energy harvesting from salty water, even though there has yet to be any large scale applications unlike PRO and RED techniques, it still has potential for further study, with one example being use of a portable battery for electricity source in remote areas to provide electricity, which is why throughout the course of this research we shall be focusing on this method of extraction of electricity

The table below provides a comparative literature review of all the relevant research papers on the existing methods and their key features and characteristics as well as how they compare to each other.

METHOD	AUTHOR	TITLE	REVIEW
Pressure Retarded Osmosis	Anthony P Straub, Ngai Yin Yip, Menachem Elimelech	Raising the Bar: Increased Hydraulic Pressure Allows Unprecedented High Power Densities in Pressure Retarded Osmosis. (2013)	• PRO method is most effective in use. • Setting up of membrane structure in seawater • Osmosis occurs through membranes • Energy from osmotic potential can be used to power turbines etc. • Highest power density obtained: 2-5W/m^2
	Jan W. Post, Joost Veerman, Hubertus V.M. Hamelers, Gerrit J.W. Euvernik, Sybrand J. Metz, Kitty Nymeijer, Cees J.N. Buisman	Salinity-gradient power: Evaluation of pressure retarded osmosis and reverse electrodialysis. (2006)	
Reverse Electrodialysis	M. Turek, B. Bandura	Renewable energy by reverse electrodialysis (2006)	• Obtain energy through chemical potential difference • Widely used – 50kW pilot plant in existence • Most expensive method due to electrodes used (large scale) • Power density of 1.2W/m^2 obtained
	Odne S. Burheim, Frode Seland, Jon G. Pharoah, Signe Kjelstrup	Improved electrode systems for reverse electro-dialysis and electrodialysis. (2012)	
Capacitive Deionisation	D. Brogioli, R. Zhao, P.M. Biesheuvel	A prototype cell for extracting energy from a water salinity difference by means of double layer expansion in nanoporous electrodes (2010)	• Newer concept, with no industrial application yet • Involves placing porous carbon electrodes in stream of salt water • Movement of ions cause charge that is stored and can be extracted • Suitable for small scale • Achieved Voltage of 0.3-0.7V • Has the potential to produce much more if used on a large scale
	M. Marino, L. Misuri, A. Carati, D. Briogli	Proof of concept of a zinc-silver battery for the extraction of energy from a concentration difference.(March, 2014)	
	M.F.M. Bijmansa, O.S. Burheima, M. Bryjakc, A. Delgadod, P.Hacke, F. Mantegazzaf, S. Tenissong, H.V.M. Hamelers	CAPMIX - Deploying Capacitors for Salt Gradient Power Extraction. (2012)	

Table 1: Comparative Literature Review

CHAPTER 3

METHODOLOGY

In this section we shall be briefly explaining the research methodology that will be employed and a general overview of the steps that will be taken in order to achieve the ultimate goal.

3.1 Research Methodology

Initially, an extensive literature review must be carried out in order to identify existing techniques and processes of energy harvesting from salty water, by collecting research papers. Understanding the integrity of the relevant systems is necessary to know the capabilities as well as advantages and disadvantages of all systems.

Identification on suitable technique – Based on the literature review, a critical analysis is done to compare and choose the most suitable technique for energy harvesting. After reviewing all the relevant methods, we have decide on to base our technique on the capacitive deionisation method, with more emphasis on electrolysis of salt water. The reasoning behind this method is that it is the most cost effective – which we can prove in the results, as well as able to achieve high efficiency in terms of power density, in addition to its being a novel method of energy harvesting compared to more conventional membrane approaches.

Experimentation and Prototype Development – To carry out the technique, we will perform experimental analysis with combination of electrodes, such as copper with aluminum, carbon with aluminum and so on to determine the best combination that achieves the most feasible amount of voltage/current and power output.

We will work to come up with a prototype which is based on [12] while still using our own techniques. The aim here is to fully understand the extent of how much power can be extracted from a certain concentration of salt water and what it can run.

Testing the output with a variety of circuits such as DC-DC boost converter with a driver circuit as well as a linear current booster would aid in our understanding of harnessing

this small scale energy. A detailed study on the operating principles of a DC-DC converter will also be performed additionally.

The prototype will be modelled as follows

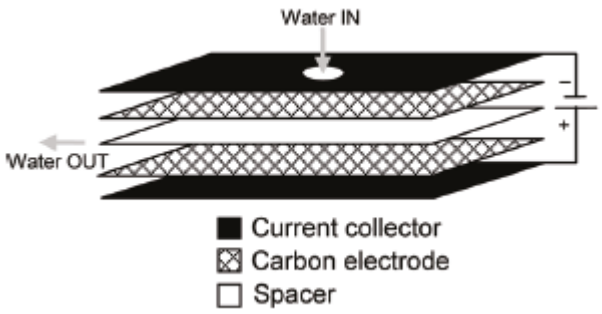

Figure 5: Prototype Design Model

In conjunction with developing the prototype, we will conduct basic experiments to identify the materials (Graphite, Magnesium, Copper) that perform better in salt water based on the output voltage obtained, which can be measured using multi-meters.

Comparative analysis will be done to compare the performance of the achieved system with existing systems [6, 12, 13]. The efficiency and rate of energy conversion with respect to concentration difference will be focused on in the results and discussion.

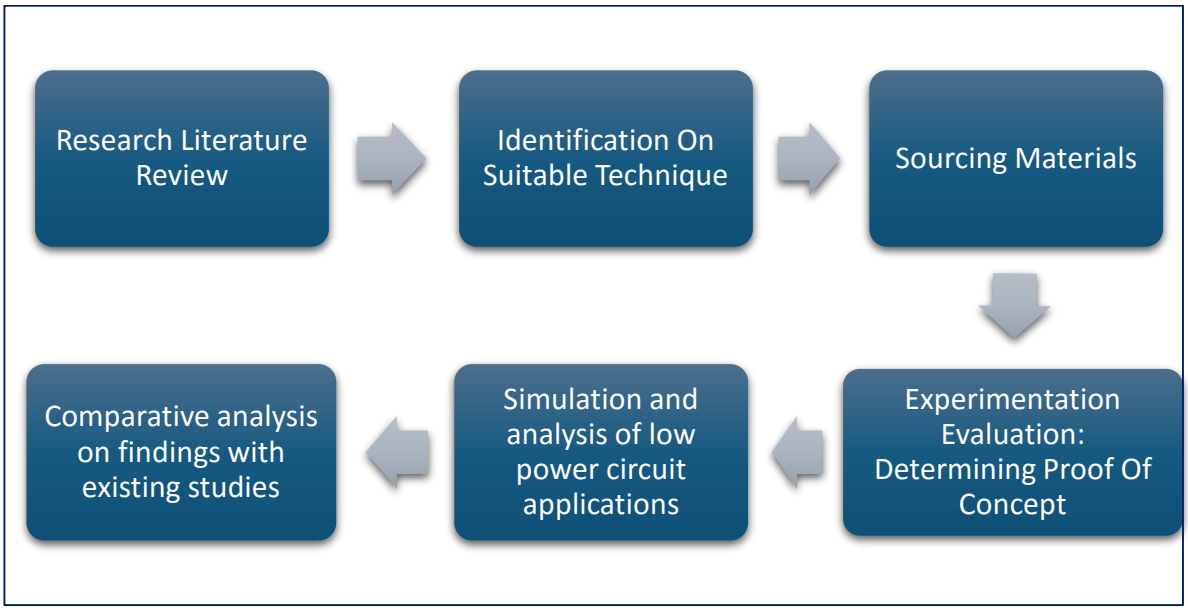

Figure 6: Research methodology process

3.2 Materials for Prototype and Experimentation

After reviewing the various material types which could be most suitable for our prototype, we move on to identifying the components for the prototype.

3.2.1 Electrodes

Figure 7: Carbon/Graphite electrodes

For the prototype we acquired graphite electrodes which is a more refined form of carbon and will work better. These electrodes have been ordered, and the parameters of it will be porosity (between 50-80%) as well as size (dimensions).

For the current collector, aluminium sheets will be used. The emphasis on these sheets is for them to be as thin as possible (between 5-10mm) thus increasing the surface area for maximum conduction.

In the sample shown below, the dimensions of the sheet is 15cm x 7.5cm and thickness is .5mm.

Figure 8: Aluminium sheet

Copper is also an electrode which is used in the experimentation. Since copper reacts readily with salt water (NaCl) to separate it into H+ and OH- ions. The copper electrodes in use for the experiment are shown below.

Figure 9: Copper Electrodes

For connections, crocodile clips were used, along with a digital multi-meter for measurements of voltage and current obtained from the setup of the experiment.

We aimed to understand, in addition to how effective the electrodes were at producing electricity, the extent of deterioration of materials and how they impact the solution and to identify if the solvents became contaminated or not.

The concentrations were varied from 1M to 3M, since the volumes of water used were small, in these situations, when the solution reaches 3M (mol) of NaCl (Sodium Chloride/Salt Solution) it becomes saturated. Increasing the amount of salt will have no further effect beyond this point.

3.2.2 Setup of Experiment

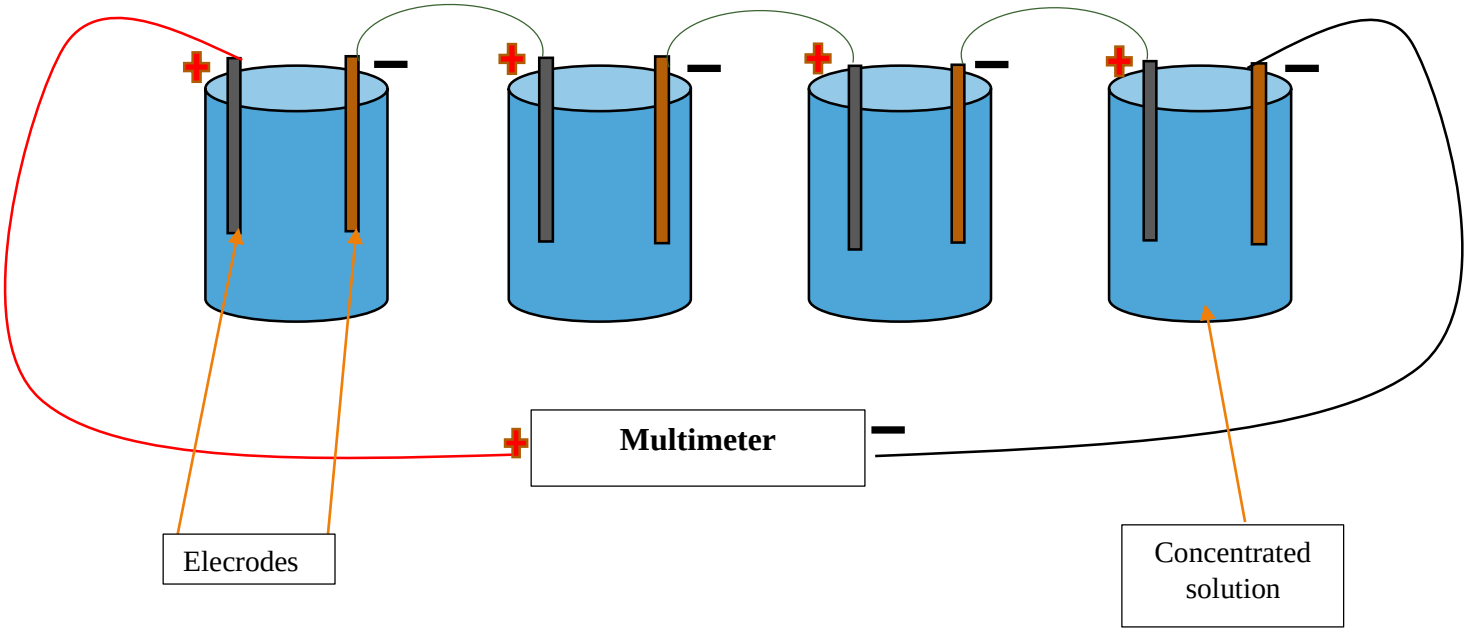

Figure 10: Experiment setup

The setup shown above is the initial arrangement of experiment to test the operating principles of energy harvesting from salt water. Through this arrangement we are able to determine the voltage/current output and then determine how much power is produced which can be used to analyse the applications of this setup. The reason it is set up in series is so that we will be able to maximise the output generated rather than simply just one pair of electrodes.

In addition, we are also studying the inclusion of DC-DC booster circuits to amplify the output in order to run certain appliances

3.3 Gantt Chart and Key Milestone

Timeline for FYP I

No.	Details/ Week		FYP 1													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Literature Review															
2	Identification of Extraction Mechanism															
3	Outline Experiment/Source materials															
4	Proposal Defense										●					
5	Documentation	Extended proposal						●								
		Interim Report														●

Table 2: Key Milestone for FYP 1

Timeline for FYP II

No	Details/ Week		FYP II														
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Prototype Development																
2	Experimental Evaluation																
3	Comparative analysis																
4	Pre-sedex											●					
5	Project Viva																●
6	Documentation	Progress Report									●						
		Draft Final Report												●			
		Dissertation (soft copy)													●		
		Technical Paper														●	
		Dissertation (hard bound)															●

Table 3: Key Milestone for FYP 2

● Key Milestone

▮ Process

CHAPTER 4

RESULTS AND DISCUSSION

After experimentation on the concept of generation of electricity from salt water, we moved on to circuit applications of low voltage/current circuits and how they can be applied to such set ups and whether they will improve the output.

4.0.1 DC-DC converter circuit

The booster circuit used was fabricated with the following specifications.

1-5V to 5V (500mA) DC-DC Boost converter step up power module.

Input voltage: 1-5V
Output voltage: 5V
Size: 17.55m x 25.22mm x 5.85mm

Figure 11: Boost converter module (PCB)

This boost converter module will be used in the circuit to analyse its effect on stepping up the voltage.

In order for us to understand, the primary circuitry of the boost converter will be described.

4.0.2 Operating Principle

The main function of a boost converter is the ability of the inductor to withstand alterations in current. During charging it acts as a load to absorb energy, while discharging it is a power source. Voltage output in the discharge phase is affected by the rate of current change.[14]

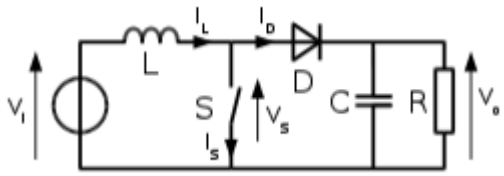

Figure 12: Boost converter schematic

The circuit has two states which is the On and Off state.

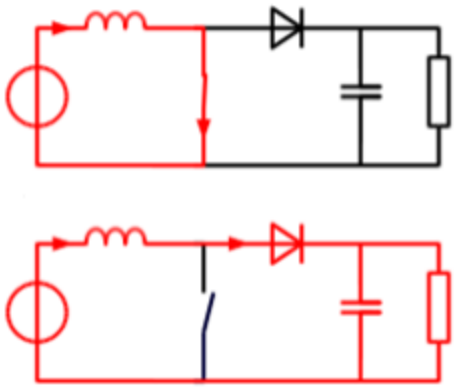

Figure 13: Two configurations of boost converter depending on state of switch

During the switching on stage, when the switch is closed, it will cause an increase in inductor current. While in the off state, the switch opens and the path offered to the inductor current is through the flyback diode, capacitor and load [15].

The input current here is the same as the inductor current, and unlike the buck converter the requirements are relaxed.

A MATLAB-Simulink simulation was done with the relevant parameters to give us further understanding.

4.0.3 Joule Thief Circuit

Another DC-DC boost converter circuit that we looked into was a Joule thief circuit that has similar operating principles with a few minor differences. Joule thief is self-oscillating voltage booster, it has the capacity to drive low voltage supplies from as small as 0.8V and convert it into a series of high frequency pulses oscillating at a higher voltage. As is the case with voltage boosting circuits, the output voltage is boosted at the expense of the loss of current.

The joule thief circuit generally consists of an input power source (in our case 1.5V), a ferrite toroid transformer for fast oscillation, a transistor and a Zener diode among other passive components. In our simulation we aimed to boost the input voltages from the extraction of energy from saltwater to up to 5V to identify if powering up of low voltage devices is possible.

4.1 Simulation

4.1.1 DC-DC Boost Converter

In SIMULINK, we aimed to design the boost converter module to implement in conjunction with the setup of the experiment.

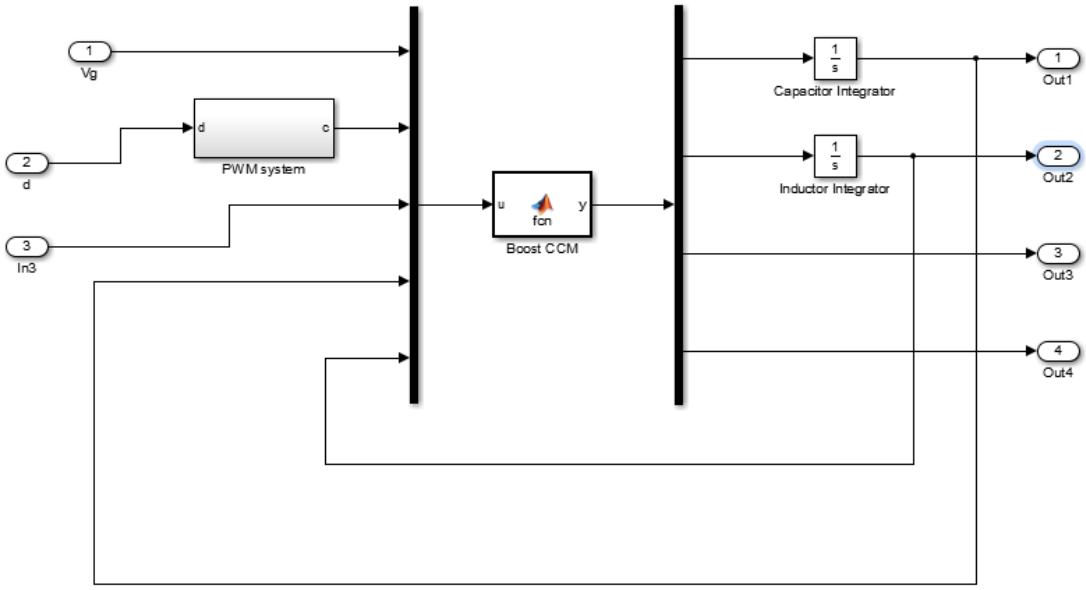

Figure 14: Boost converter subsystem block

Based on Figure 14, which is the initial boost converter subsystem block. The inputs in this system are:

- Input voltage (Vg)
- Voltage control (duty cycle) d
- Load current I out

The outputs in the system for the converter are:

- Capacitor voltage (Vc)
- Inductor current (iL)
- Output voltage (Vout)
- Input current (Ig)

The Boost CCM is a MATLAB function to process the input, and it contains the coding for the parameters and variables of the output.

The PWM model is also an integral part of the system as it regulates the output by varying the on time of switching and the switching frequency. This control circuit has functions such as maintaining an output voltage (constant) even though there is fluctuation in the input voltage, which is common during the experimentation as over time, the electrolysis causes the electrodes to react thus slowly reducing the amount of power generated with time.

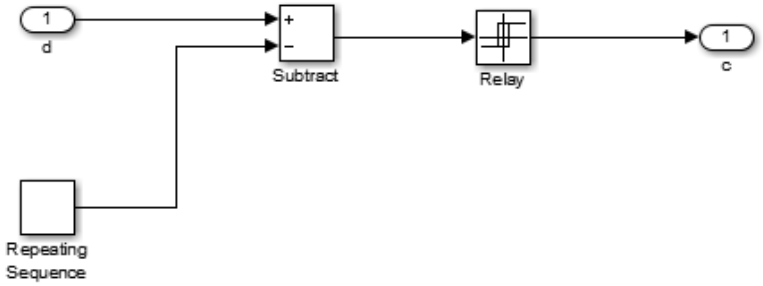

Figure 15: PWM model for the boost converter

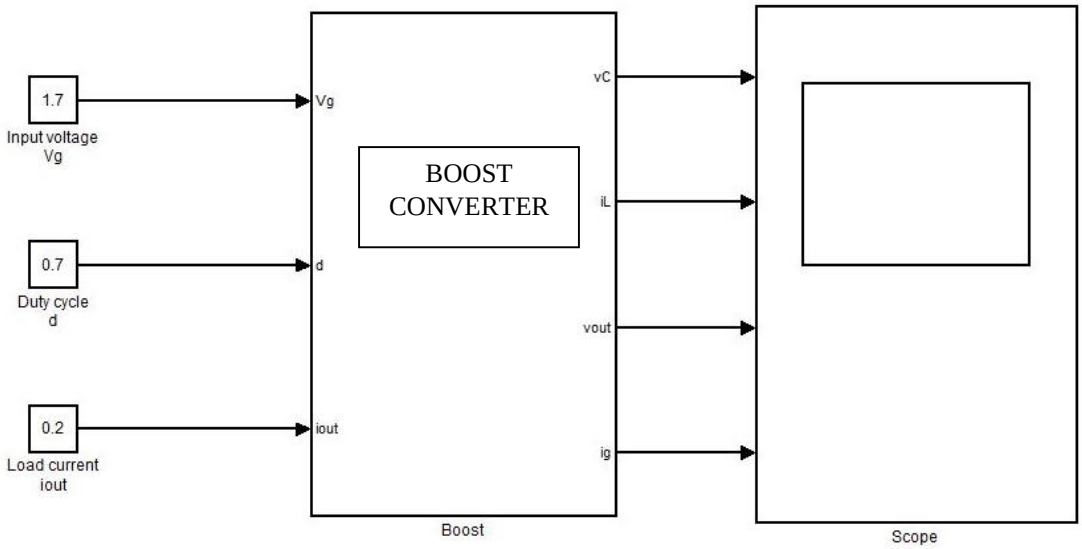

Figure 16: Finalised boost model

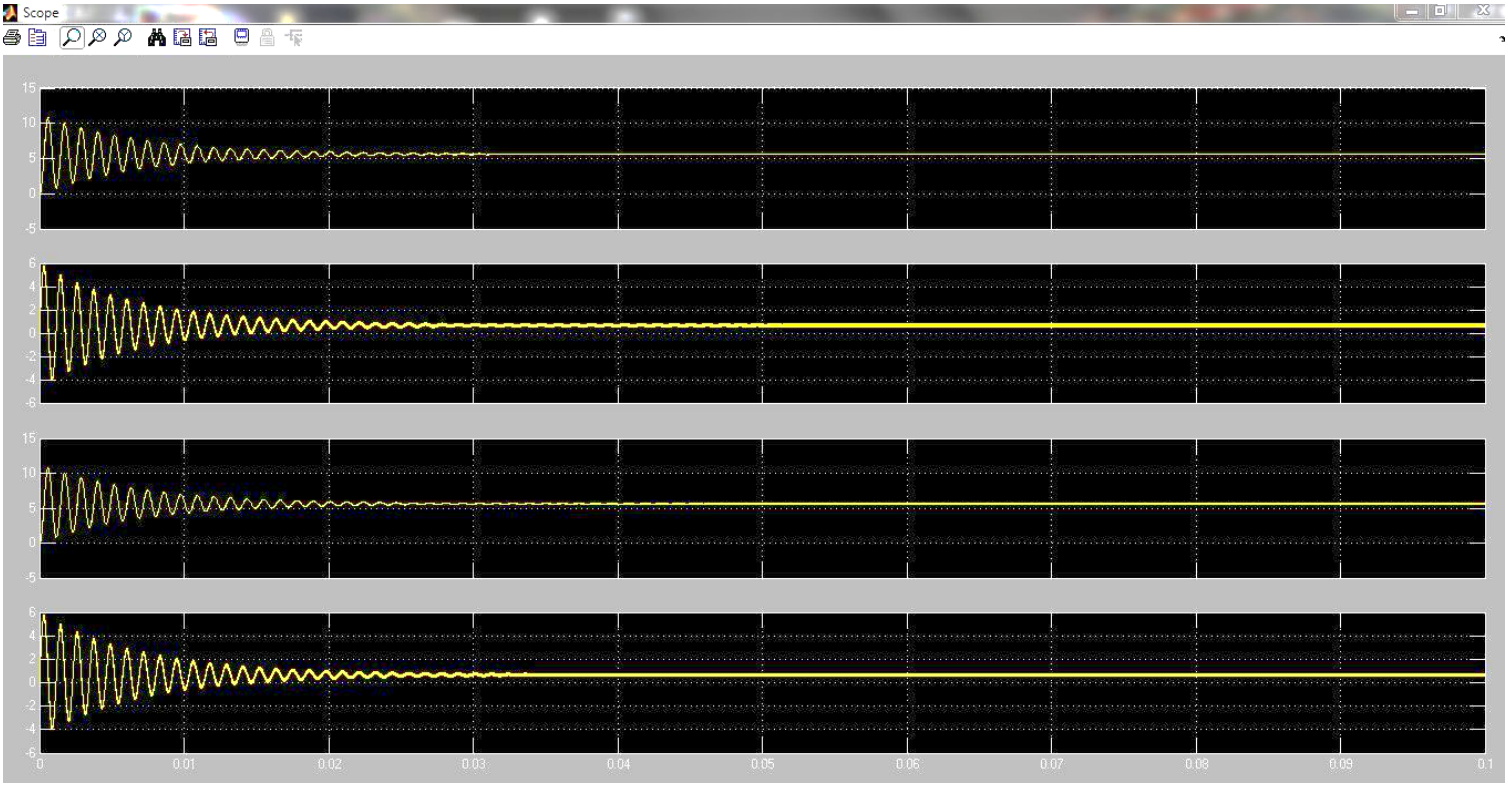

Figure 17: Scope of Output

Based on the scope above you can see that the output graphs display:

1. Capacitor voltage
2. Inductor current
3. Output voltage
4. Input current

What we can distinguish from the results, is that due to the fluctuation of the input voltage and currents, there is a ripple in the component characteristics as they try to achieve steady state. As the desired output voltage is 5V, initially there is some fluctuation as the input voltage varies from between 1.5-1.7V.

What is interesting to note is that the current generation is not so high, as we are dealing with low power applications, and in this module, the current is actually slightly reduced in order to step up the voltage to 5V.

4.1.2 Joule Thief Circuit

The joule thief circuit was simulated in LT Spice in combination with the experimental results to identify their effectiveness,

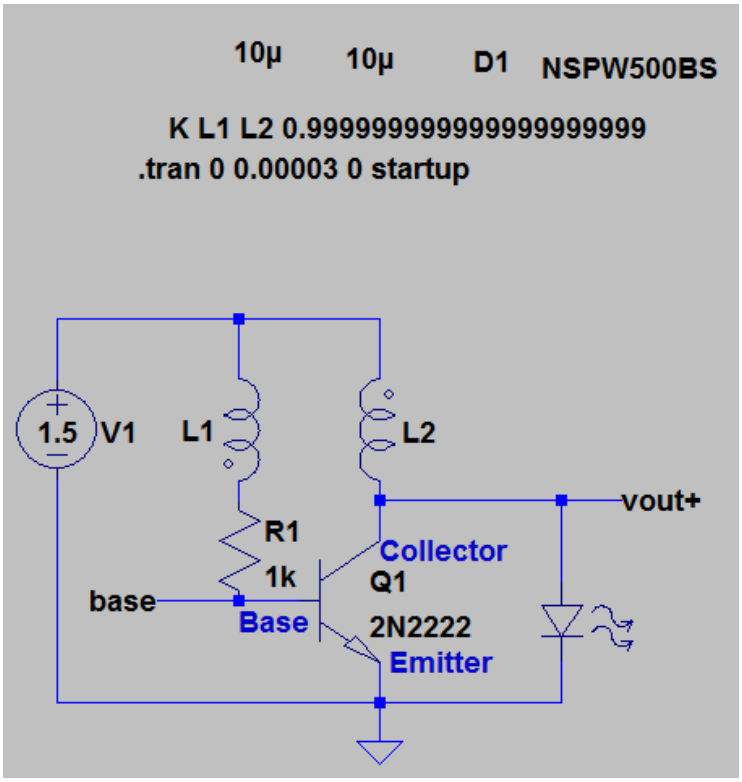

Figure 18: LT Spics Simulation of Joule Thief Circuit

A significant difference in our design of the joule thief in comparison with conventional circuits was the addition of an extra capacitor and Zener diode to help protect the transistor from high voltage spikes that can occur if the circuit is switched on when no load is present. The Zener diode limits how high the output voltage can reach but in turn protect the transistor, ensuring it has a longer life.

The results of the simulation are shown below.

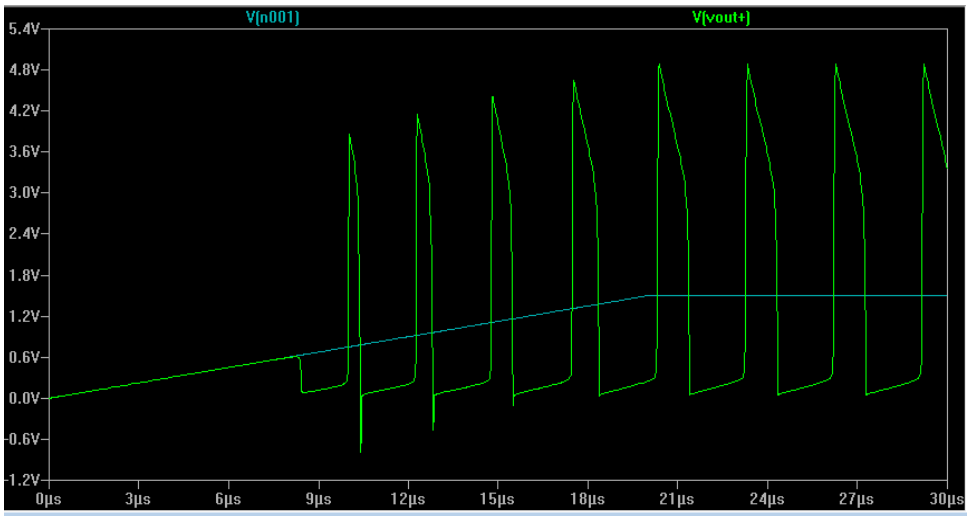

Figure 19: Simulation showing input voltage vs output voltage

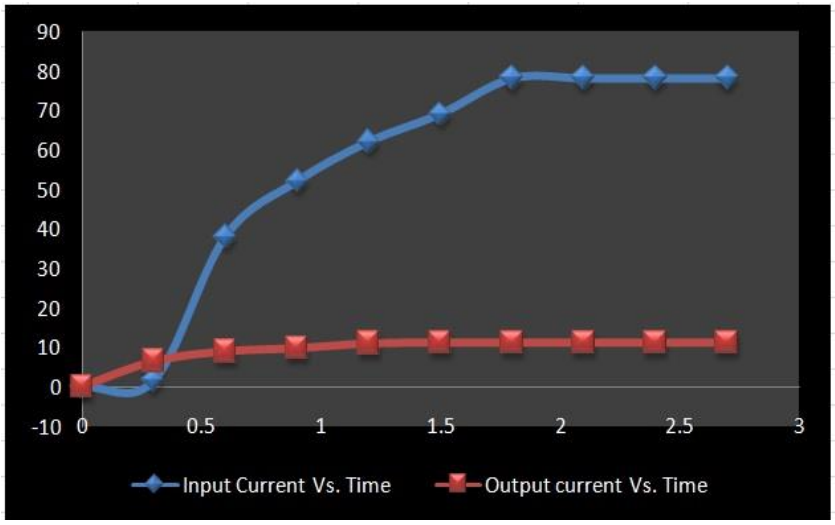

Figure 20: Simulation showing input current vs output current

The graphs above – Figure 19 and Figure 20, represent the voltages at the input and output stages as well as the current at both input and output stages with respect to time.

The voltage was measured in volts (V), while the current was measured in milliamps (mA)

4.2 Experimentation Results

The experiment was carried out and the results are presented as follows:

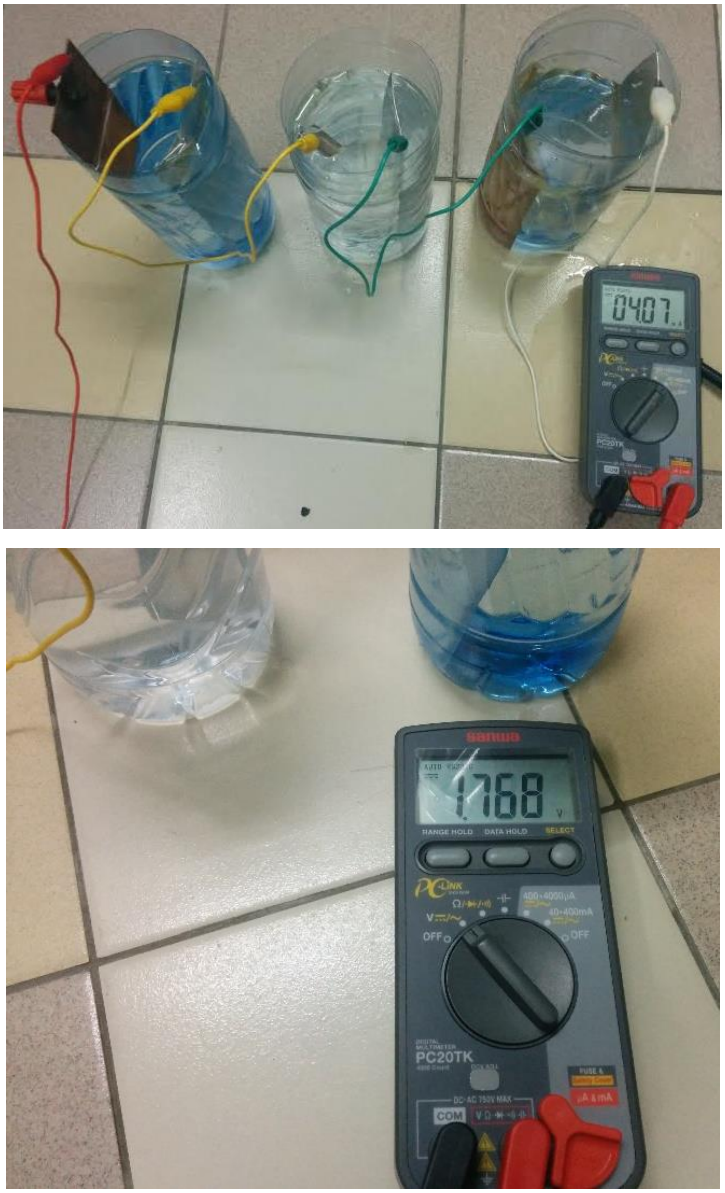

Figure 21: Typical setup of experiment/Readings

Experiment 1– **Carbon/Copper**

Table 4: Experiment between Carbon/Copper

Readings (min)	**Volume of Water (ml)**	**Mass/Concentration of Salt**	**Voltage (V)**	**Current (mA)**	**Power (W/m^2)**
1	750 ml	50g Conc = 1.150 M	1.05 V	0.42 mA	4.41×10^{-4}
2			1.02 V	0.40 mA	4.08×10^{-4}
3			1.00 V	0.40 mA	4.00×10^{-4}
4			0.95 V	0.38 mA	3.61×10^{-4}
5			0.92 V	0.37 mA	3.404×10^{-4}
8			0.85 V	0.33 mA	2.805×10^{-4}
10			0.81 V	0.28 mA	2.268×10^{-4}
12			0.80 V	0.30 mA	2.400×10^{-4}

Experiment 2 – **Carbon/Aluminium**

Table 5: Experiment between Carbon/Aluminium

Readings (min)	**Volume of Water (ml)**	**Mass/Concentration of Salt**	**Voltage (V)**	**Current (mA)**	**Power (W/m^2)**
1	750 ml	50g Conc. = 1.150 M	1.850 V	0.75 mA	1.3875×10^{-3}
2			1.842 V	0.73 mA	1.290×10^{-3}
3			1.821 V	0.70 mA	1.247×10^{-3}
4			1.800 V	0.68 mA	1.224×10^{-3}
5			1.775 V	0.66 mA	1.1715×10^{-3}
8			1.765 V	0.65 mA	1.147×10^{-3}
10			1.752 V	0.50 mA	0.876×10^{-3}
12			1.750 V	0.50 mA	0.875×10^{-3}

Experiment 3 – **Copper/Aluminium**

Table 6: Experiment between Copper/Aluminium

Readings (min)	Volume of Water (ml)	Mass/Concentration of Salt	Voltage (V)	Current (mA)	Power (W/m^2)
1	750 ml	50g Conc = 1.150 M	1.45 V	4.10 mA	5.95×10^{-3}
2			1.42 V	4.07 mA	5.78×10^{-3}
3			1.40 V	3.95 mA	5.50×10^{-3}
4			1.37 V	3.80 mA	5.21×10^{-3}
5			1.33 V	3.50 mA	4.66×10^{-3}
8			1.30 V	3.32 mA	4.32×10^{-3}
10			1.27 V	3.10 mA	3.9×10^{-3}
12			1.25 V	3.10 mA	3.875×10^{-3}

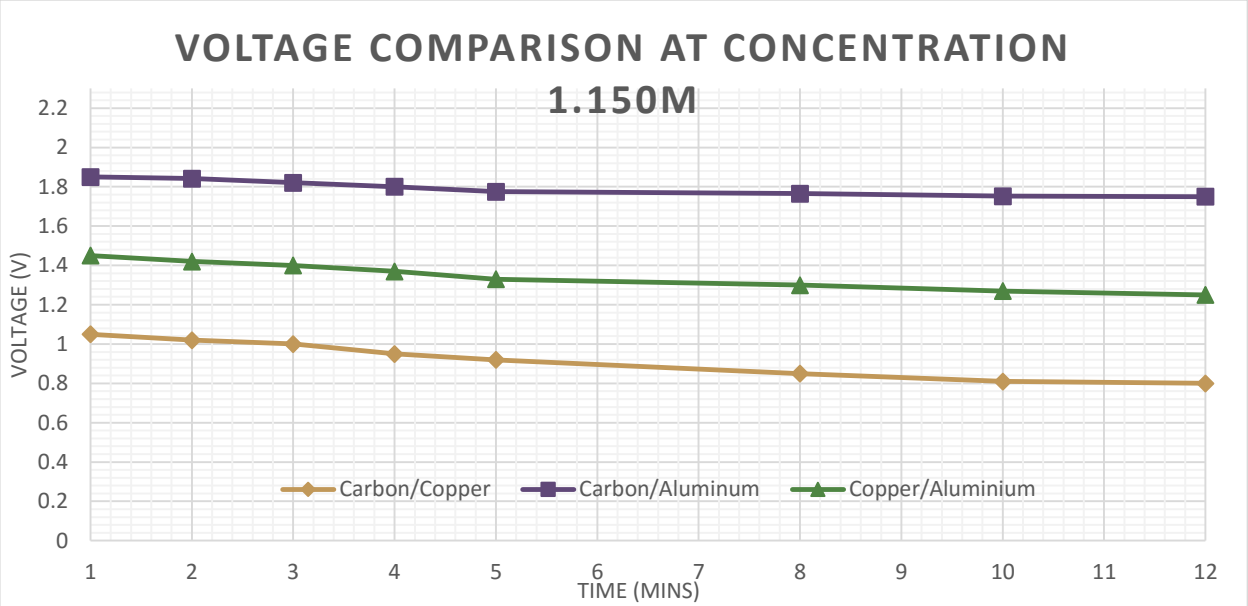

Figure 22: Voltage comparison at concentration 1.150M

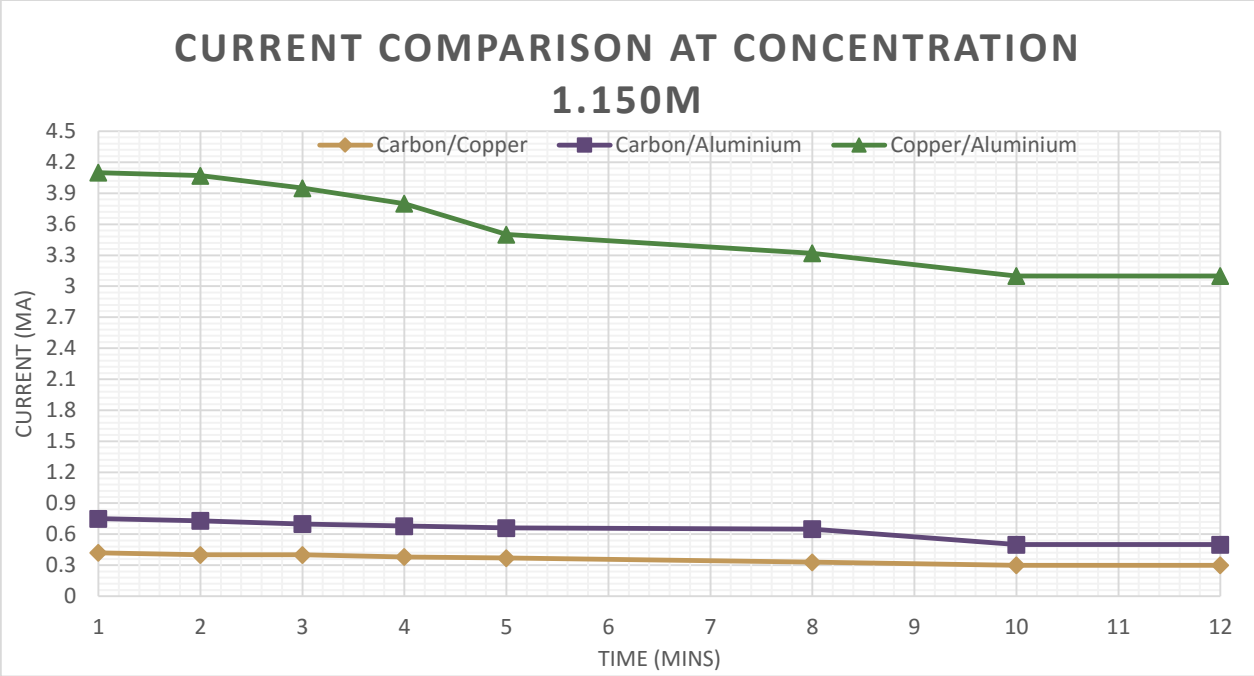

Figure 23: Current comparison at concentration 1.150M

Experiment 1.1 – **Carbon/Copper** (saturated solution)

Table 7: Experiment between Carbon/Copper 2.875M

Readings (min)	**Volume of Water (ml)**	**Mass/Concentration of Salt**	**Voltage (V)**	**Current (mA)**	**Power (W/m^2)**
1	500ml	70g Conc = 2.875 M	0.85 V	0.75 mA	6.375 x10^{-4}
2			0.78 V	0.74 mA	5.722 x 10^{-4}
3			0.72V	0.735 mA	5.292 x10^{-4}
4			0.70 V	0.720 mA	5.04 x10^{-4}
5			0.65 V	0.70 mA	4.55 x10^{-4}
8			0.62 V	0.64 mA	3.698 x10^{-4}
10			0.55 V	0.62 mA	3.41 x10^{-4}
12			0.43 V	0.575 mA	2.4725 x10^{-4}

Experiment 2.1 – **Carbon/Aluminium** (saturated solution)

Table 8: Experiment between Carbon/Aluminium 2.875M

Readings (min)	**Volume of Water (ml)**	**Mass/Concentration of Salt**	**Voltage (V)**	**Current (mA)**	**Power (W/m^2)**
1	500ml	70g Conc. = 2.875 M	1.750 V	3.20 mA	5.6×10^{-3}
2			1.920 V	3.18 mA	6.106×10^{-3}
3			1.880 V	3.15 mA	5.922×10^{-3}
4			1.850 V	3.12 mA	5.772×10^{-3}
5			1.820 V	3.12 mA	5.678×10^{-3}
8			1.800 V	3.10 mA	5.58×10^{-3}
10			1.780 V	2.97 mA	5.2866×10^{-3}
12			1.730 V	2.95 mA	5.104×10^{-3}

Experiment 3.1 – **Copper/Aluminium** (saturated solution)

Table 9: Experiment between Copper/Aluminium 2.875M

Readings (min)	**Volume of Water (ml)**	**Mass/Concentration of Salt**	**Voltage (V)**	**Current (mA)**	**Power (W/m^2)**
1	500 ml	70g Conc = 2.875 M	1.12 V	15.65 mA	0.0175
2			1.10 V	15.6 mA	0.0172
3			1.25 V	15.55 mA	0.0194
4			1.40 V	15.53mA	0.0217
5			1.55 V	15.45 mA	0.0239
8			1.53 V	15.37 mA	0.0235
10			1.50 V	15.35 mA	0.0230
12			1.48 V	15.20 mA	0.0225

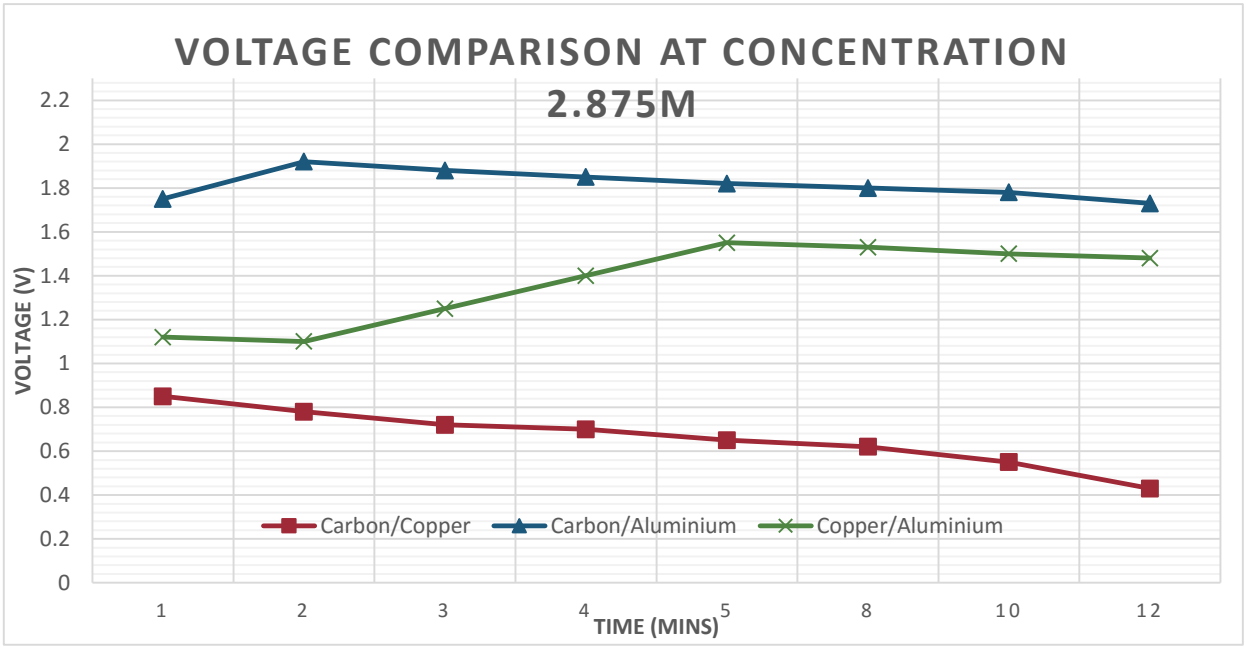

Figure 24: Voltage comparison at concentration 2.875M

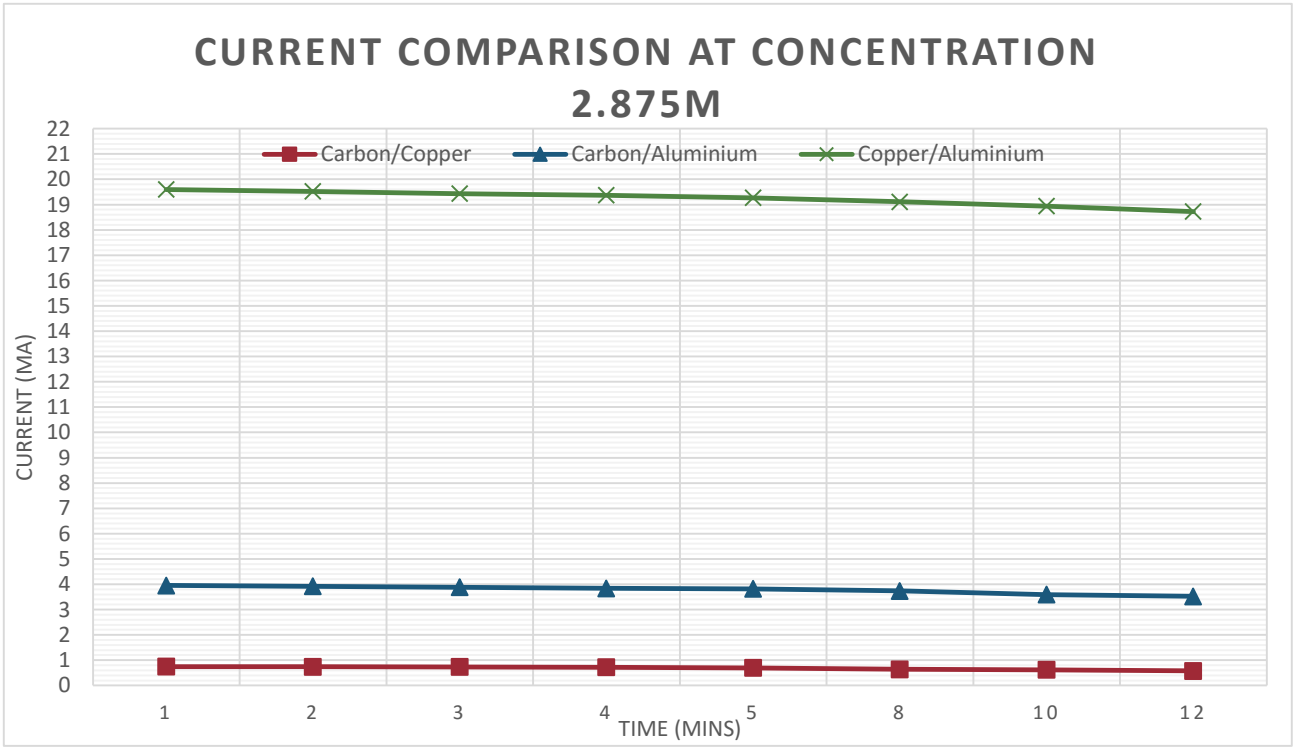

Figure 25: Current comparison at concentration 2.875M

4.3 Discussion and Analysis

This section will aim to analyse the results of the experiments carried out.

Experiment Set A

Based on the Table 4, 5, 6 and figures 19, 20, 21 which is analysing the effect at concentrations of 1.150M we can observe that the most effective electrode combination is between Copper and Aluminium, mainly from the increased current output it shows when compared to Carbon/Copper and Carbon/Aluminium. Though Carbon/Aluminium shows the highest voltage output out of the three sets (between 1.7-1.8V), the current output is much less (1mA) which makes it an unreasonable pick.

Carbon and Copper showcases by far the worst power generations in terms of both voltage and current. What is interesting to note, is that a concentration of 1.150M of solution was utilised in order to determine the power outputs for a solution that is neither saturated nor completely distilled.

Experiment Set B

Based on Table 7, 8, 9 and figures 22, 23, 24 which analyses the effect at 2.875M. The experimental results for the saturated solution further proves that the most effective electrode combination is Copper/Aluminium with higher current outputs being produced at more concentrated solutions.

We can see that in general, the more concentrated solution provides a better power output, and maximum of 15.65mA was achieved initially. Carbon and Aluminium continued to provide the highest voltage from the sets (1.92V), but still did not provide sufficient current as compared to Copper and Aluminium.

One major observation is that over time, the electrodes went through a slow disintegration process, though Copper reacted the most and there was significant amounts of Copper in the solution. This can cause the water to be contaminated, though if the set up was placed in a flowing mechanism or even the sea, the solution will be continually renewed thus avoiding this issue.

Our analysis on the simulations of the DC-DC boost converter show that with a low voltage input of less than 2V (1.1 – 1.8V) we can boost it to a reasonable value of 5V at the expense of a drop in current. Since the power output has to be maintained throughout, current generation is affected, and current output is generally low.

For the joule circuit, the simulation run on LT Spice was also able to reach an output voltage of 5V from the input voltage of the experiments, but what was quite noticeable from the current graphs was that a drop of nearly 85% was observed from the current output, as compared to the input. From nearly 90mA, there was a decrease to about 10mA.

Throughout the testing phase of using the boost converter module, we were unable to fully achieve the 5V output, due to the input current not being sufficient even though there is a significant voltage output.

What can be understood is that in order to achieve an increased current output would be to employ more sets of electrodes and solutions in series and use larger electrodes which would increase the surface area of the reaction between the materials and salt ions which translates to an increase in energy generated.

4.3.1 Further Work

Based on the initial experimentation, we can see that best combination which provides substantial voltage/current output is the experiment involving copper and aluminium. Carbon and copper proved to be the least effective while carbon and aluminium even though it provided a substantial voltage, did not achieve enough current.

As shown, all parameters were kept constant, with the only variables being the electrode materials.

Our next step is to connect the setup with the boost converter and then observe the output voltage/current to verify is a valid amount of energy can be harvested from salt water.

The boost converter simulation model is also a representation of understanding how the circuit can aid in amplifying the complete setup or if it is not feasible at all for the model,

and the operating principles of the circuit give us more of an in depth analysis of the phenomena.

Since it is observed that the current output is relatively low, we will aim to rectify this by studying the implementation of a linear current booster and how it can help in this scenario of application.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

The development of a system for energy harvesting from salt water with the ability to extract as much electricity from the concentration gradients between fresh and salty water is required, as it would help industries in developing more efficient power plants.

Study, experimentation and prototype design will aim to be carried out to determine the viability of the proposed technique and determine the amount of electricity that can be produced as well as devices that can be powered.

In the upcoming weeks we aim to successfully construct the prototype and test the voltage output obtained so that it can be used as a benchmark for moving further.

The further analysis of the data acquired through experimentation of such a system is to find how to upscale the prototype to industry level while maintaining the same or higher level of output power.

A recommendation for further improvement would be to use Graphene as the main electrode material. Graphene is basically a more pure form of bonded carbon in sheet form, and this is deemed as potentially the element of the future as its extreme purity opens up possibilities in energy extraction and various other situations.

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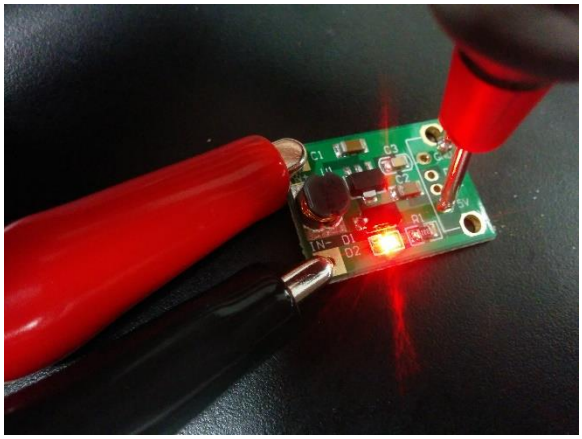
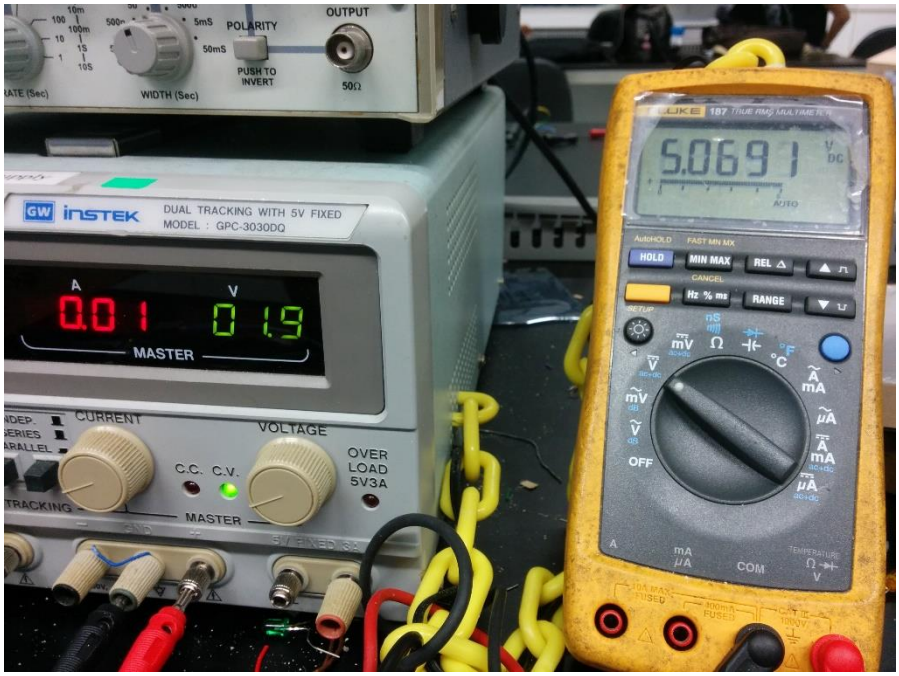
APPENDICES



Boost Converter Module testing



Testing the output from boost converter module

MATLAB Code for Boost converter CCM function

```
function y = CCMBoost(u,L,C,RL,Ron,Resr)

% Inputs:
% u = [Vg D iout v_C i_L]
%
% Parameters:
% L, RL, C, Resr, Ron
%
% Outputs:
% y = [dv_C/C di_L/L Vo ig]

Vg = u(1);                  % Input voltage
D = u(2);                   % Switch control
iout = u(3);                % Load current
vC = u(4);                  % Capacitor voltage
iL = u(5);                  % Inductor current

dbar = 1-D;

% State equations
Vo = vC + Resr*((iL*dbar) - iout);          % Output voltage
Ig = iL;                                    % Input current
iC = (iL*dbar) - iout;                      % Capacitor current
vL = Vg - (Vo*dbar) - iL*((Ron*D) + RL);    % Inductor voltage

% Output
y = [iC/C vL/L Vo Ig];
```