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EE313 Analogue Electronics Project
Group 3 Final Report:
Hydroelectric Power Generation

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Abstract

The increase in modern energy harnessing techniques and applications have been thoroughly researched and utilised in the renewable energy space. Power generation using renewable energy has an upward trend of becoming the next safe and reliable power system with various environmental benefits. The focus for power generation in this case will be hydroelectric power, a robust and versatile solution for homes which need various appliances to be powered. The opportunity to design, implement and analyse a hydroelectric system to increase the use of renewable energy will become much more efficient with greater research and testing. This report outlines the design process for the creation of a hydroelectric power system using LTSpice simulation. This report will include a breakdown of our system along with theoretical information supported by the simulation testing. This report aims to provide both a fundamental understanding of the system and a step-by-step process of implementing it using software. The simulation of the system is comprised of various power analysis techniques such as rectification and DC-DC conversion, both used to demonstrate the system's function and to investigate the viability of implementing a fully functioning hydroelectric power system.

Acknowledgements

A special thanks to Mr. Rytis Beinarys, the team facilitator, for the advice and support, over the duration of the project.

The authors would also like to thank the other facilitators, Dr. Bob Lawlor for all advice and feedback leading up to this report.

1. Introduction

This project was chosen by the group as part of the Maynooth University Electronic Engineering Analogue Electronics 2 module (EE313). The group was tasked with choosing a project relating to the module's content. Energy harnessing was selected as the focal theme with the objective of investigating whether we could convert the renewable energy from a water source into useable electricity for different types of applications. The group decided to look further into current methodologies in use to achieve this task and plan to design a system which can answer our research question.

In this report, the focus will be on the literature review and the background, methodology and the current progress made behind this topic with the hope that our research can be used to solve the problem statement.

1.1 Project Motivation

The main motivation for this project came from the fact that harnessing energy from renewable sources is one of the biggest sectors in science and engineering. This aspect attracted the group as hydroelectric power has a positive trajectory with its environmental impact, lower cost benefits and maintenance. The most well-known example of this will be the hydroelectric dams that are used to supply power grids for houses and large electrical appliances. The group does not expect to look at this type of power scale, but the research will be included to convey the principles of operation.

1.2 History & Background

The history of waterpower can be traced all the way back to the sixth millennium BC up to the earliest known being from as far back as the second millennium BC.

- Qanat system - Ancient Persia [1]
- Turpan water system - Ancient China [2]
- Water wheels/water mills - India, Imperial Rome, China (Han Dynasty) [3]
- Water clocks - Ancient Greece [4]

Water clocks could be said to be one of the oldest uses of waterpower, as well as one of the oldest time-measuring instruments, as one was discovered dating all the way back to 1500 BC in the tomb of Amenhotep I. The main use for the water clock was to keep time, as indicated to in the name we use for them today. But they were originally called clepsydras. It operated by regulating a flow of water/liquid into or out of the vessel, and from there the amount would be measured. This is only one of many early uses of waterpower.

Water wheels were invented in ancient Greece and Rome in the thirteenth century BC. They existed for uses on irrigation of fields. There are many different variations of uses for a water wheel. [5]

1.3 Modern Uses of Hydropower

Hydroelectric power has become more and more integrated into our lives as many countries have achieved in harnessing electrical energy from the energy of flowing water. The most obvious is seen in the form of dams but every year there are further developments in technology where new materials and improved components have led to new harnessing techniques. This can be seen especially in undersea currents being used to spin turbines, new nontoxic materials and quitter motors have allowed for these to be placed in any underwater environment. Figure 1 shows the kW/m that can be generated from oceans around the world. As you can see that the potential kW/m is greatest I the middle of the ocean, seen at the south pole and the mid-Atlantic Ocean. But receiving this power at a cost-effective manner is difficult at this moment but new technologies and companies such as SeaGen are speeding this up trend. [6]

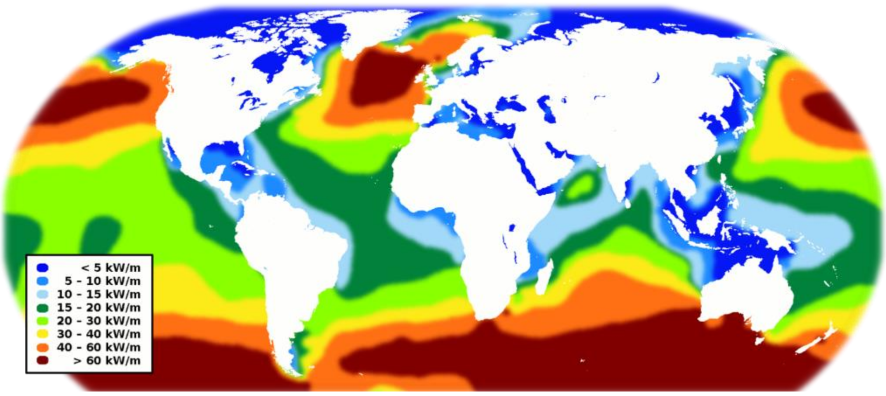

FIGURE 1: WORLD WAVE ENERGY RESOURCE MAP [7]

Hydroelectricity is now known as the most powerful source of renewable energy [8].

1.4 Advantages & Disadvantages

Hydroelectric power must be analysed from a pros & cons perspective with demonstrating the positive and negative effects of this system. This section will describe the different advantages and disadvantages of hydroelectric power.

1.4.1 Advantages of Hydroelectric power

Hydroelectric power has many advantages over its renewable energy counter parts. This gives us plenty of reason to use hydroelectric power over other sources of renewable energies. Here are a few reasons as to why hydroelectric power is advantageous to us:

- Hydroelectric power uses the energy of running water, without affecting the volume of water, to produce electricity.
- Hydroelectric power facilities do not release pollutants into the air or water and their developments do not generate toxic by-products.
- There is more flexibility in the storage of hydroelectric power making it more economical. Dams have massive reservoirs which can be thought of as a giant battery.
- Hydroelectricity guarantees energy and price stability. Since water is a domestic resource, unlike fuel or natural gas, the market price will not fluctuate.
- Hydroelectric power helps fight climate change and the hydroelectric life cycle produces very little greenhouse gasses. [9]

1.4.2 Disadvantages of Hydropower

The same as other sources of renewable energies, they have many advantages but that also comes with its fair share of disadvantages. Although renewable energy is what is best for our environment and betterment of it, there are some aspects that they can still have a negative impact on. Here are a few examples of the disadvantages of hydroelectric power:

- Hydroelectric power facilities affect land use, natural habitats, important natural areas etc.
- Hydroelectric power is hydrology dependent. The system depends on precipitation levels, causing instability on a year-to-year basis.
- Hydroelectric power facilities can lead to a loss of fish habitat and lead to fish entrapment or restrict their passages.
- Hydroelectric power facilities can cause a change to water levels, water temperature and the rivers flow, which could in turn harm plants and animals native to the river and on land. [9]

2. Hydroelectric Power - Methods & Principles

There are many methods of harnessing energy from bodies of water and converting it into electricity. Just as bodies of water can be categorised as freshwater or saltwater, we will categorise energy harnessing methods as offshore or inland.

2.1 Inland Methods

All methods of generating electricity from inland water sources, though differing in scale and layout, use the same principles that will be explained in Section 2.3 of using height difference and flow rate of the water source to turn its kinetic energy into electricity. There are 4 kinds of inland hydropower plants (HPPs) [10].

2.2.1 Storage Hydropower Plants

Also known as impoundment hydropower plants, these plants are the largest and most common hydroelectric generators in the world [11]. A dam is used to impede the flow of water and fill a reservoir that suspends the water above the downstream current. The reservoir acts as an energy storage. The flow rate of the water into the turbines can then be controlled by gates, and since the height difference between the reservoir and the downstream current is a constant and known value, the amount of power generated is easily controllable and extremely stable. Thus, these power plants can maintain constant power outputs, or the output can be varied to meet peak demands.

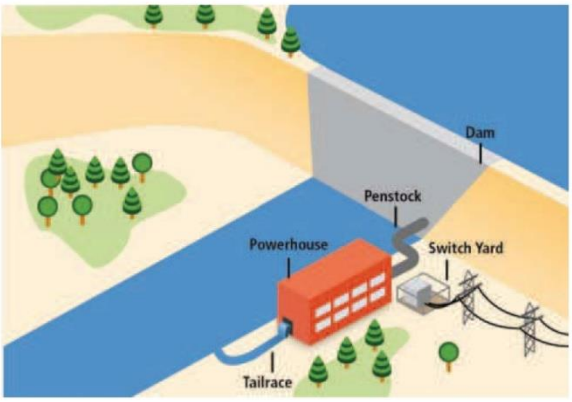

FIGURE 2: STORAGE HPP [12]

2.2.2 Pump Storage Hydropower Plants

These plants do not produce any net power and are exclusively used as an energy storage [13]. During times of excess grid power, water is pumped from a lower reservoir to a higher reservoir. When grid demand exceeds supply, water can flow from the higher reservoir to the lower one much like regular storage plants as described above. Due to losses caused by friction in pipes and inefficiencies in turbines, these plants are net consumers of power. However, due to their ability to store large amounts of energy and their ability to quickly meet peak grid demands, they are used extensively. Pump storage is the largest capacity form of grid storage currently available.

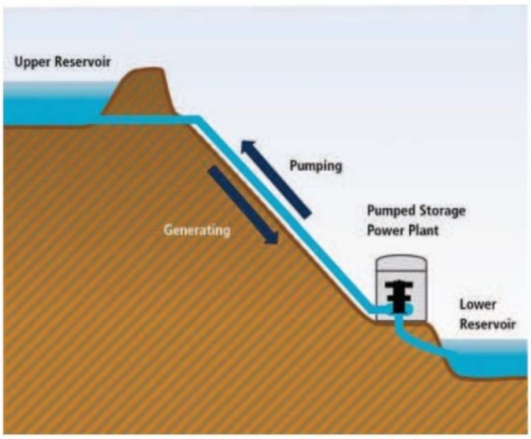

FIGURE 3: PUMP STORAGE HPP [12]

2.2.3 Run-of-River Hydropower Plants

Run-of-river (RoR) plants use the natural height difference and flow rate of bodies of water to produce power [14]. They have small intake basins with little to no storage capacity. Again, the height difference is a constant and known value, however these plants rely entirely on the natural flow rate of the body of water. This means that while the amount of power generated may vary daily, monthly and/or seasonally, this system has no means of responding to changes in grid demands.

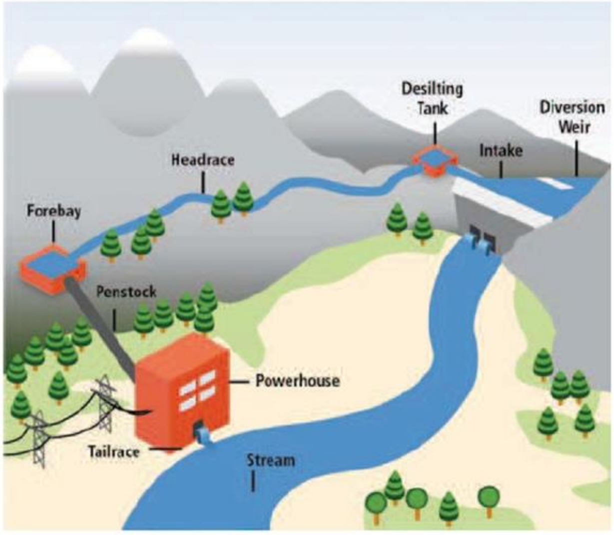

FIGURE 4: ROR HPP [12]

2.2.4 In-Stream Hydropower Plants

This is a new technology and is not widely used yet. It differs from the previous schemes in that it does not utilise the head and flow rate of the stream. Instead, it uses a hydrokinetic turbine to harness the kinetic energy of the stream [12]. Effectively, it is a wind turbine submerged underwater. However, as water is over 800 times denser than air, the blades of these turbines can be very small and still produce vast amounts of power.

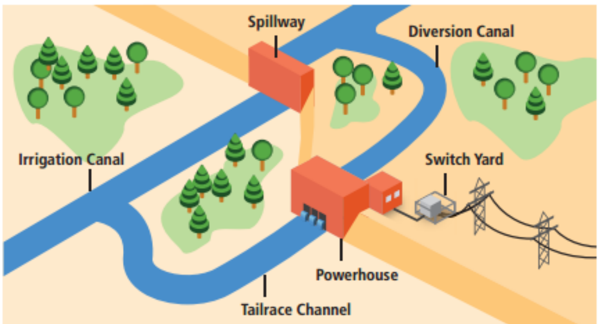

FIGURE 5: IN- STREAM HPP [12]

2.2 Offshore Methods

Though hydroelectricity has existed for a long time, it is only recently that the world has begun to harness power from the sea. The following methods either have not yet or are only beginning to be utilised on a large scale by multiple nations.

2.2.1 Tidal Barrage

Much like a storage HPP, these power plants utilise tidal range (the height difference between low and high tides) to generate electricity [15]. A barrage is constructed across an inlet of an ocean bay or lagoon that forms a tidal basin. Gates in the barrage allow water to enter the basin at high tide and then only allow the water to drain through a turbine at low tide. Pumps may be used to increase the head of the water in the basin and the flow of water leaving the basin can be controlled. Some plants use two-way generation where, as the tide comes in and fills the basin, it passes through turbines just as it does as the tide goes out.

This method is both reliable and predictable as the height of the tides are determined by the gravitational effect the Sun and Moon have on our oceans.

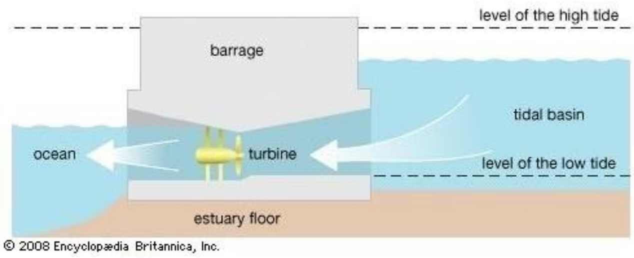

FIGURE 6: TIDAL BARRAGE [16]

2.2.2 Tidal Turbines

These turbines are the exact same as the ones that in-stream hydropower plants use. They harness the hydrokinetic energy of the tidal currents as they pass through the turbine blades. They can be fixed to the seabed or float on the surface with the turbine submerged and only moorings attached to the seafloor.

As with tidal range, the power output is only reliant on the cycles of the Earth, Moon and Sun and is therefore predictable hundreds of years into the future.

For the sake of brevity, underwater turbines that rely on ocean current are also included under this heading because they function in the exact same way except, they are reliant on many other factors such as: temperature difference, salinity, the Coriolis effect and many others [17].

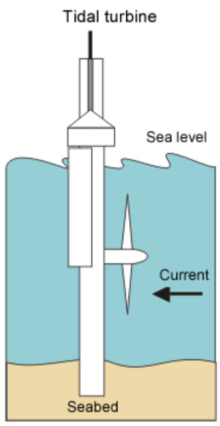

FIGURE 7: TIDAL TURBINE [17]

2.2.3 Wave Energy

There are many methods of harnessing energy from the ocean's waves. So many, in fact, that to go into details for each one would be beyond the scope of this project. So again, for the sake of brevity, they will be summarised briefly below.

- Point absorbers harness energy through the relative motion between a body that moves in response to the waves and an immobile structure [18].

- Surface attenuators consist of multiple segments (or a single, long, flexible segment) floating on the surface of the sea. They use the rise and fall of the waves to create a flexing motion that may be converted into rotation or drive hydraulic pumps to generate electricity [19].
- Oscillating water columns use wave action to pressurise air in a chamber and force it through an air turbine [19].
- Overtopping devices allow wave action to fill a reservoir and then generate electricity much like the tidal barrage or the storage HPP [19].
- Oscillating wave surge converters are like surface attenuators in that they consist of a free moving body and a fixed body and generate power based on the relative motion between the two. The difference being that this time it is driven by the horizontal motion of the waves (surge) [19].

Wave energy is much less predictable than tidal range or tidal stream energy as it is reliant almost entirely on wind strength.

2.2.4 Ocean Thermal Energy Conversion

This method utilises the temperature difference between warm, surface seawater and cold, deep seawater to vaporise either a working fluid, such as ammonia, with a low boiling point (closed-cycle) [20] or the warm surface water itself (open-cycle) [21] to turn a turbo-generator.

In the closed-cycle system, the working fluid is infinitely useable as it simply passes through 2 heat exchangers to continuously turn the turbine. The first heat exchanger has the surface water pumped through it to vaporise the fluid, the second has the deep water pumped through it to condense the fluid. [20]

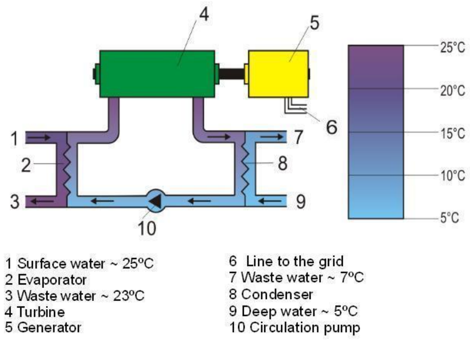

FIGURE 8: CLOSED-CYCLE OTEC [22]

The open-cycle system simply pumps the surface water into a low-pressure chamber, where it boils, turns the turbine, and is then passed through a condenser with the deep water. This method produces desalinised water suitable for drinking, irrigation, or aquaculture. [21]

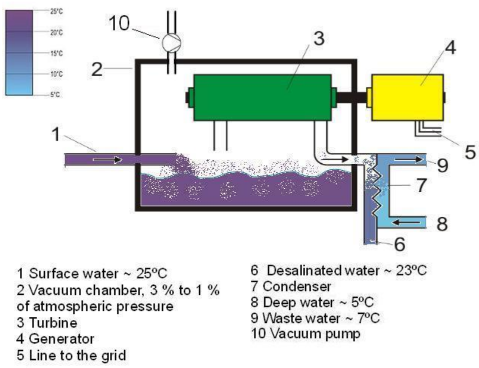

FIGURE 9: OPEN-CYCLE OTEC [22]

Because this energy is continuously available, it can provide for base-load supply.

2.2.5 Salinity Gradient Power

There are technically 2 ways of generating power using salinity gradients, however the most modern and the one most likely to be used on a large scale is reversed electrodialysis [23]. In this method, seawater and freshwater are passed through a stack of alternating cation and anion exchange membranes. The difference in chemical potential between the salt and fresh water creates a voltage over each membrane. The process operates through the difference in ion concentration instead of an electric field.

2.3 Working Principle of Hydroelectricity

As seen in the previous sections, there are many methods of harnessing power from water, but the most common way is to harness its potential energy. The water has potential energy due to it being suspended some height above the ground. Thus, the equation to find the potential energy of a mass of water is given by:

$$\boldsymbol{E = mgh}$$

EQUATION 1: POTENTIAL ENERGY

Where: ***m*** is the mass of the water (kg), ***g*** is the acceleration due to gravity (m/s^2) and ***h*** is the water's height (m).

However, not all the potential energy of the water can be harnessed because turbines and pipes cannot be 100% efficient and we are not taking the water in from its surface. Thus, the equation for available power becomes:

$$\boldsymbol{W = \eta \dot{m} g \Delta h}$$

EQUATION 2: POWER FROM WATER (1)

Where: ***W*** is the power output (W), ***η*** is the efficiency of the system (no unit), $\boldsymbol{\dot{m}}$ is the mass flow rate (kg/s), ***g*** is the acceleration due to gravity and ***Δh*** is the height difference between the inlet and the outlet (referred to as the head).

Mass flow rate is not a measurable quantity and so, the equation is further developed to:

$$\boldsymbol{W = \eta \rho \dot{V} g \Delta h}$$

EQUATION 3: POWER FROM WATER (2)

Where: ***ρ*** is the density of water (kg/m^3), which may vary depending on its environment, and $\boldsymbol{\dot{V}}$ is the volumetric flow rate (m^3/s) (referred to as the flow rate).

2.3.1 Theoretical Maximum Efficiency

There is no theoretical maximum efficiency for this kind of energy harnessing. This is because there are no thermodynamic or chemical processes necessary for the conversion from potential energy to kinetic energy to electric energy. There is also no established conversion efficiency limit (like the Betz conversion efficiency limit for wind turbines) [24], however there is an efficiency limit for open-channel systems such as tidal turbines [25]. The reason this does not apply to closed channel systems is because the water has no other path to go other than through the turbines. It is however impossible to achieve 100% efficiency due to the fact it would require water to come to a complete stop within the turbine. Large hydro plants can operate at up to 90% efficiency, water to wire [10, p. 96].

2.3.2 Turbines

Turbines are mechanical devices used to capture energy from a flowing fluid and convert it into useful work. The work produced by the turbine can be used for generating electrical energy with the help of a generator. There are two different types of turbines “impulse turbines” and “reaction turbines”.

The impulse turbine generally uses the velocity of the water to move the runner and discharges to the atmospheric pressure. The water pressure pushes each bucket on the runner. An impulse turbine is generally suitable for high head, low flow applications. There are a few turbines such as a Pelton Wheel, a Turgo Wheel or a Crossflow Turbine in this category.

The Pelton wheel has one or more jets discharging water into the turbine casing into the buckets. These buckets “catch” the water and allows the blade to turn or spin so that the water jet would be directed on the next blade causing the turbine to spin.

FIGURE 10: THE PELTON WHEEL

A Turgo Wheel is a variation on the Pelton whose shape generally resembles a fan blade (runner blades) that are closed on the outer edges. The Turgo Wheel is deigned to have a higher speed than the Pelton Wheel. The jets are aimed to strike the plane of the runner on one side and it exists on the other side, therefore the flow rate is not limited by the discharge of the fluid interfering with the incoming jet spray [26]

A Turgo turbine can have a smaller diameter runner than a Pelton for an equivalent power, if we were to use an impulse turbine this would be ideal for our project as for the small amount energy generated, we would not want to be wasting it due to external sources.

FIGURE 11: THE TURGO WHEEL

These are examples of impulse turbines. We will now look at an example of a reaction turbine. A reaction turbine develops power from the combined action of pressure and moving water. The runner is placed in the water stream allowing the water to flow over the blades rather than striking them directly. Reaction turbines are used for sites with a lower head and a higher flow.

A crossflow turbine allows the water to flow through the blades twice. The flow of water is directed on top of the blades, where the blade directs the water to another blade opposite. Passing through the runner twice provides additional efficiency. When the water leaves the runner, it helps to clean of small debris from the blades. The crossflow turbine is a low-speed turbine that is suited for locations with a low head but high flow [27].

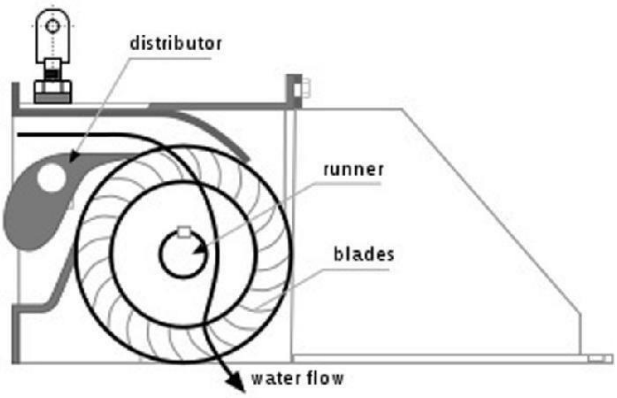

FIGURE 12: CROSSFLOW TURBINE

We can assume that the head in our theoretical location for this project will be low, but our flow will be high this makes the crossflow turbine ideal for this project.

2.3.3 Transformers

Transformers are electrical devices consisting of two or more coils of wire used to transfer electrical energy by the changing of its magnetic field [28]. A transformer operates on the principals of "electromagnetic induction", a coil of wire wrapped around the core can induce a voltage on another coil located close to it. Transformers are mainly used for increasing or decreasing the voltage and current supplied, without modifying its frequency, or the amount of electrical power being transferred from one winding to another.

The transformer consists of two coils, the “Primary winding” and the “Secondary winding”. The primary side is where the voltage source is located, and the secondary side is where the output voltage is delivered. They are wrapped around a closed core usually made of iron. The two coil windings are electrically isolated from each other but are magnetically linked through the common core allowing electrical power to be transferred from one coil to the other. When an electric current is passed through the primary winding, a magnetic field is created which induces a voltage in the secondary winding as shown in Figure 13.

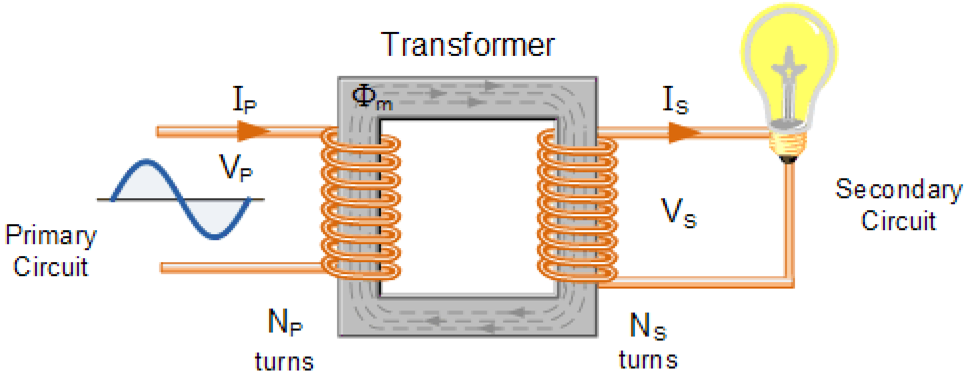

FIGURE 13: TRANSFORMER DIAGRAM [28]

The turns ratio (***n***) is very important for transformers as it displays the relationship of the input and output voltage. Its calculated as expressed in *equation 1*, where N_P and N_S are the number of primary and secondary windings respectively, and V_P and V_S are the voltages in the primary and secondary windings, respectively. This equation can also be used to determine the volage on either the primary or secondary windings.

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = n$$

EQUATION 4: TURNS RATIO EQUATION

Now the number of windings in the secondary coil determines the voltage which is outputted. A single-phase transformer can operate to either increase or decrease the voltage applied to the primary winding. When a transformer is used to “increase” the voltage on its secondary winding it is called a step-up transformer, the turn ratio would have a larger number on the right side when calculated. When it is used to “decrease” the voltage on the secondary winding it is called a step-down transformer, the turn ratio would have a smaller number on the right side when calculated [29].

With any power producing plants, transformers are essential. These power plants would need to step down the voltage before allowing it onto the grid. Voltage on the grid is carried at higher levels than the voltage levels in our homes, this reduces the current and any losses from $I^2 * R$, this means that before the grid voltage is distributed to houses it must be stepped down by another transformer. In an ideal transformer, the power available in the secondary winding will be the same as the power in the primary winding, they do not change the power only the voltage to current ratio. So, in an ideal transformer the Power Ratio is equal to one as the voltage multiplied by the current remains constant. So as the transformer can step up and down voltages it cannot do this to power.

$$Power_{Primary} = Power_{Seconday}$$

$$V_P I_P cos\emptyset_P = V_S I_S cos\emptyset_S$$

Where $\emptyset_P$ is the primary phase angle and $\emptyset_S$ is the secondary phase angle. So, doubling the voltage would decrease the current by and half while delivering the same amount of power to the load, and reducing the power loss by a factor of four from $I^2 * R$ [28].

To ensure our application has the correct voltage we can design a transformer to meet the specified voltage, by stepping it up or down, to meet our requirements.

2.3.4 Generators

Arguably the heart of the hydroelectric power plant is the generator. Most hydropower plants have several of these generators. The shaft of the turbine rotates when the turbine blades harness the kinetic energy of the flowing water, which in turn is connected to a generator. The basic process of generating electricity is to rotate a series of magnets inside coils of wire. This process moves electrons, which produces electrical current this is called electromagnetic induction.

The modern-day generator works on the principle of electromagnetic induction discovered by Michael Faraday. Faraday discovered that the above flow of electric charges could be induced by moving an electrical conductor, that contains electrical charge, in a magnetic field. This movement creates a voltage difference between the two ends of the electrical conductor or wire, which in turn causes the electric charges to flow, thus generating electric current.

The equation for calculating the electromotive force can be seen from Equation 5: Faraday's Law, which is the rate of change of the magnetic flux where **ε** is the induced voltage (EMF), **N** is the number of turns, **Φ** is the magnetic flux measured in weber, **B** is the external magnetic field and **T** is the time measured in seconds.

$$\boldsymbol{\varepsilon = N\frac{d\Phi_B}{dt}}$$

EQUATION 5: FARADAY'S LAW

3. Rectification

Rectification is how an alternating current (AC) is converted so that it is usable for direct current (DC) requirements [30].The flow of AC is constantly changing direction, and for this reason, it is unsuitable for a device that requires a DC supply. Therefore, to preform rectification, a diode known as a rectifier is often needed such that it allows the flow of current to occur in one direction only. There are two different types of rectification – full-wave and half-wave. Figure 14 shows an illustration of the half-wave rectification.

3.1 Half-wave rectification

In a half-wave rectification of a single-phase supply, either the positive or the negative half of the AC wave is passed while the other half of the wave is blocked. Because of this effect, the mean voltage is lower as only half of the input wave is used. The half-wave rectification circuit requires a single diode and a single-phase supply [31]. Rectifiers yield a unidirectional but pulsing direct current signal. They produce far more ripple (periodic variation) than full-wave rectifiers. Filtering may be required to eliminate harmonics from the output. The primary reason for the output to have a rectified positive half cycle is because the diodes will be placed in forward biased.

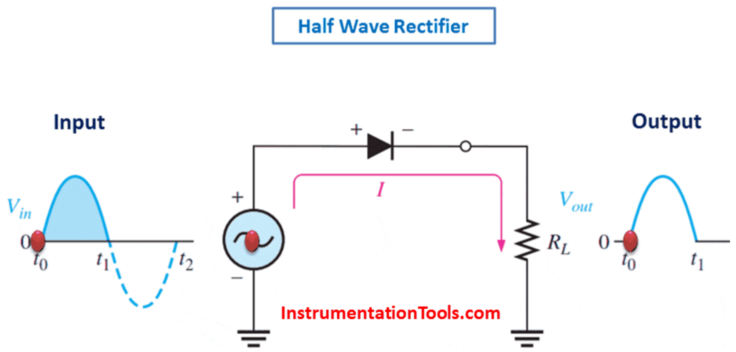

FIGURE 14: HALF WAVE RECTIFICATION [32]

The RMS of the output voltage V_{rms} is half of the peak voltage V_{Pk}, the derivation for the RMS is mathematically described below and the equation is followed by the derivation as indicated in Equation 6.

Mathematical Derivation:

$$I_{rms} = \sqrt{\int_0^{2\pi} \frac{I_{peak}^2 \sin^2\theta}{2\pi} d\theta}$$

$$I_{rms} = \frac{I_{peak}^2}{2\pi} \int_0^{2\pi} \frac{1 - \cos 2\theta}{2} d\theta$$

$$I_{rms} = \frac{I_{peak}^2}{4\pi}(2\pi)$$

$$I_{rms} = \frac{I_{peak}}{2}$$

$$V_{rms} = I_{rms} \ x \ R_l$$

$$V_{rms} = \frac{V_{peak}}{2}$$

EQUATION 6: MEASURING RMS VOLTAGE

Measuring the DC output of a half wave rectifier can be described mathematically with the following derivation, followed by the equation indicated in Equation 7:

Mathematical Derivation:

$$V_{DC} = \frac{V_{peak}}{2\pi} \int_0^{\pi} \sin(\theta)\, d\theta$$

$$V_{DC} = \frac{V_{peak}}{2\pi}[-\cos(\pi) + \cos(0)]$$

$$V_{DC} = \frac{V_m}{2\pi}(2) = \frac{V_m}{\pi}$$

EQUATION 7: MEASURING DC OUTPUT VOLTAGE

3.2 Full-wave rectification

A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) [31]. It converts both polarities of the input waveform to a pulsating DC and yields a higher average output voltage because of this. Two diodes and a transformer, or four diodes in a bridge configuration and an AC signal is needed. The primary reason for the output to have a rectified positive half cycle is because the diodes will be placed in forward bias.

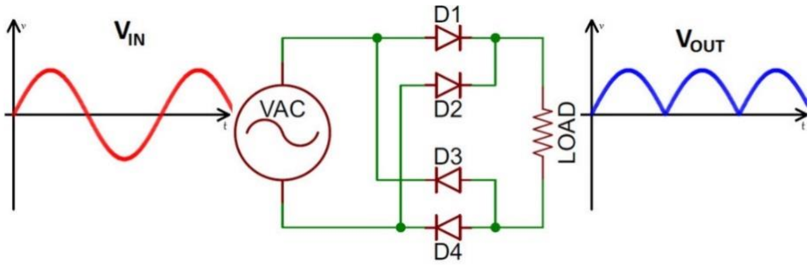

FIGURE 15: FULL WAVE RECTIFICATION [33]

The primary application of the rectifier is for AC to DC converting. Therefore, they can be found in power supplies of nearly all electrical devices. A full-wave rectification should be used for the receiver, which should drive the current load. Measuring the DC output (no-load) for a sinusoidal input voltage can be described mathematically the derivation and the equation indicated in Equation 8:

Mathematical Derivation:

$$V_{DC} = \frac{V_{peak}}{\pi} \int_0^{\pi} sin(\theta)\, d\theta$$

$$V_{DC} = \frac{V_{peak}}{\pi} [-cos(\pi) + cos(0)]$$

$$V_{DC} = V_{av} = \frac{2(V_{peak})}{\pi}$$

EQUATION 8: AVERAGE OUTPUT FOR FULL WAVE RECTIFICATION

The RMS of the output voltage V_{rms} is half of the peak voltage V_{Pk}, the derivation for the RMS is mathematically described below and the equation is followed by the derivation as indicated in Equation 9.

Mathematical Derivation:

$$V = V_{max} \sin\theta$$

$$V^2 = V_{max}^2 \sin^2\theta$$

$$|V^2|_{Avg} = \int_0^{2\pi} \frac{V_{max}^2 \sin^2\theta}{2\pi} d\theta$$

$$|V^2|_{Avg} = \frac{V_{max}^2}{2\pi} \int_0^{2\pi} \frac{1 - cos2\,\theta}{2} d\theta$$

$$|V^2|_{rms} = \frac{V_{max}^2}{4\pi} (2\pi)$$

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}}$$

EQUATION 9: RMS FOR FULL WAVE RECTIFICATION

Whenever a current supply has been rectified, there will be a small change in voltage usually in the form of ripples. This is where smoothing is necessary using a capacitor. The use of a capacitor in this situation will reduce the number of ripples by smoothening them out, leaving a current flowing in one direction only.

3.3 Smoothing Capacitor Ripple Voltage

There will usually be a ripple on the output of a signal, this is the perfect application for using a smoothing capacitor to reduce ripple. To solve this problem, calculations must be made to estimate values for peak-to-peak ripple. An overly large capacitor will add extra weight, cost, and size. While a capacitor that is too small will lead to a much worse DC output voltage regulation. Figure 16 shows how smoothing works aside a normal oscillating waveform.

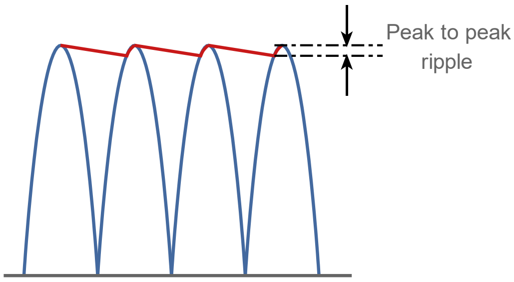

FIGURE 16: RIPPLE VOLTAGE SMOOTHING [34]

Equation 10 mathematically describes how the peak-to-peak ripple difference can be calculated, where V_{pk} is the peak voltage, pk_{ripple} is known as the peak ripple, I_{load} is known as the load current, f is the ripple frequency and C is known as the capacitance.

$$V_{pk} - pk_{ripple} = \frac{I_{load}}{fC}$$

EQUATION 10: SMOOTHING

The amount of ripple in a smoothed rectified signal is given by the Equation 11, where R_{load} is known as the overall resistance of load for the supply.

$$R_{load} * C > \frac{1}{F}$$

EQUATION 11: RIPPLE GIVEN

The choice of value for the capacitor can have a very large effect on the signal and this value needs to be chosen carefully to fulfil the design requirements. The main requirement being a value must be chosen so that its time constant is much longer than the time interval between successive peaks of the rectified waveform. For cases where the ripple is small compared to the power supply it is possible to calculate the V_{ripple} from certain circuit conditions [35].

$$V_{ripple} = \frac{I_{Load}}{2FC}$$

EQUATION 12: FULL-WAVE RECTIFICATION

$$V_{ripple} = \frac{I_{Load}}{FC}$$

EQUATION 13: HALF-WAVE RECTIFICATION

3.4 Ripple Current

Two major specifications of a capacitor are its capacitance and its working voltage which is also known as the maximum continuous voltage that can be applied to a capacitor without failure during its longevity period [36]. However, applications where large levels of current may flow, a third parameter is of importance, this parameter is known as the Maximum Ripple Current [31]. The ripple current in a capacitor is not always equal to the supply current. There will always be two cases, capacitor discharge current and capacitor charging current.

On a discharge cycle, the maximum current supplied by the capacitor occurs at the output of the rectifier as the signal falls. At this point all current from the circuit is supplied by the capacitor. This is equal to the full current of the circuit.

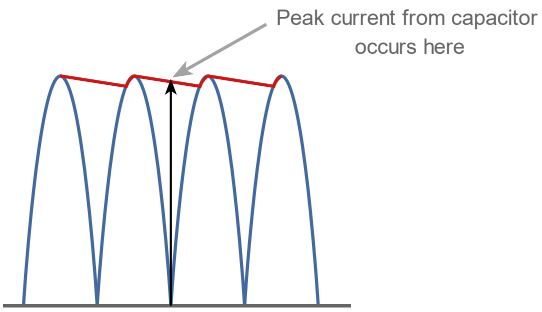

FIGURE 17: DISCHARGE CURRENT [34]

On the charge cycle of the smoothing capacitor the capacitor needs to replace all the lost charge, but it can only achieve this when the voltage from the rectifier exceeds that of the smoothing capacitor. It occurs over a very short period of the cycle. The current is much higher at this period. The larger the capacitor, the shorter the charge period [31].

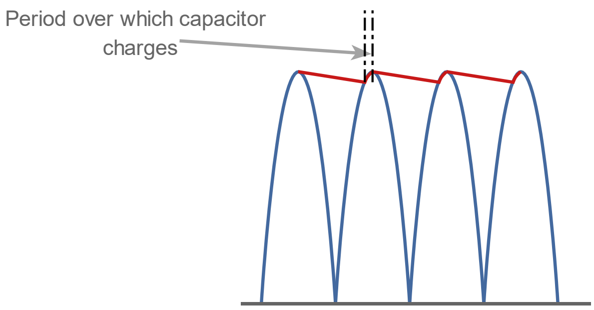

FIGURE 18: CHARGING CURRENT [34]

4. Power Conversion and Analysis

Power Conversion is an important process that goes into most engineering projects that are related to energy. The focal point of this project is Hydroelectric Power Generation and there will be a constraint that does not allow the system to reach its desired form and value. This section will look at the possible DC-DC converters that can be used for the power conversion analysis and the inverter which will return the DC voltage back to its original form, in this case the original desired form would be AC.

4.1 DC-DC Converters

DC-DC converters are used many times in certain engineering applications and projects to efficiently regulate the voltage from an input source [37]. DC-DC converters are known as high switching frequency circuits which usually will consist of electronic components such as inductors, capacitors, diodes, and transistors (switching device).

4.1.1 Buck Converter Analysis

The buck converter will be the one of the DC-DC converters that are considered in this report as it is used to lower the output voltage with a given voltage input. This type of converter is also known as a step-down voltage converter, stepping down voltage while supplying more current from its input to its output. Buck converters are highly efficient and can achieve efficiency values greater than 90% [38].

The Ideal Switch

An Ideal switch is a switch which does not consume or dissipate any power from its source. In the case of a buck converter, this type of switch can be used to reduce the DC voltage through rapid switching. It is important to bear in mind that in practice, transistors and diodes will be used to execute fast switching. Figure 19 shows the switch in two positions. When the switch is in position 1, $v_s(t)$ is equal to the source voltage v_g. When the switch is in position 2, the output voltage goes to zero.

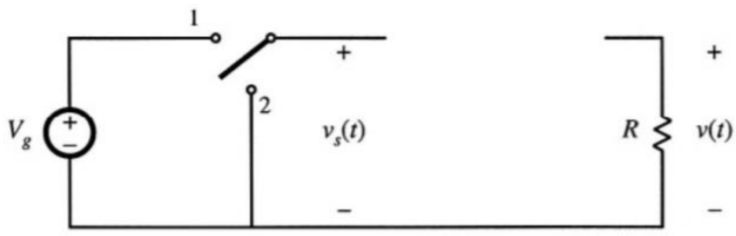

FIGURE 19: IDEAL SWITCH [39]

The switching frequency fs in the circuit is equal to the inverse of the switching period Ts, depending on the switching speed of the transistor, Ts can vary within a range. The duty cycle (D) is known the ratio of time a load or circuit is on compared to the time the load or circuit is off. Therefore, the switch is in position 1 for DT_S and in position 2 during the remainder of the switching period $D'T_S$. To find the DC component of the circuit, mathematically finding the average value by integrating can give the following formula:

$$\boldsymbol{v_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)\mathrm{dt} \;\rightarrow\; \frac{1}{T_s}\left(DT_s v_g\right) = Dv_g}$$

EQUATION 14: VOLTAGE OUTPUT WITH RESPECT TO DUTY CYCLE

Equation 14 describes the mathematical approach to solving the DC component of the circuit with a buck converter [38]. Figure 20 will conceptually show how the ideal switch output voltage waveform works with the duty cycle in each position, it is important to keep in mind that this is the steady state analysis.

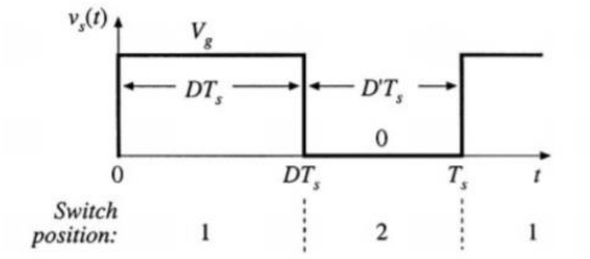

FIGURE 20: OUTPUT VOLTAGE WAVEFORM OF THE IDEAL SWITCH [39]

Output Voltage

In the calculation of the output voltage, the rule is that the duty cycle must be adjusted such that, $v_s = Dv_g$. The duty cycle is multiplied by the source voltage altering the output voltage. Figure 21 will show the buck converter using its "lossless" elements will build a network with zero power dissipation allowing for linear control of the output [39].

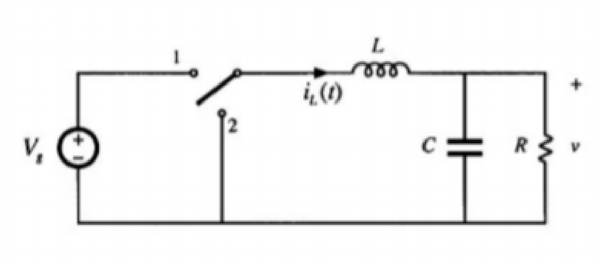

FIGURE 21: LOSSLESS CIRCUIT [39]

Figure 22 will describe how the equation $V = Dv_g$ can be used to determine the DC output voltage, V. It can be seen from the figure that the buck converter has a linear control characteristic, where the output voltage is less than or equal to the input voltage such as (0 < D < 1) [38].

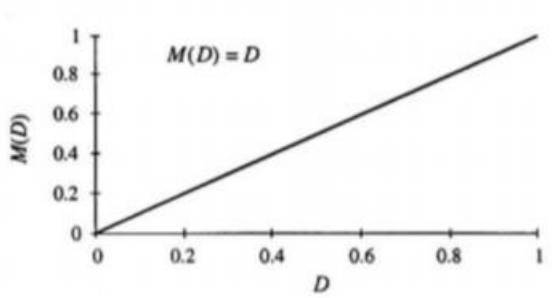

FIGURE 22: LINEAR RELATIONSHIP OF THE DUTY CYCLE [40]

4.2.2 Boost Converter Analysis

A boost converter will be the other DC-DC converter to be considered in this report as this step-up converter produces an output voltage larger than the input voltage. A boost converter contains the following electronic components: an inductor, a switch, a diode, and a capacitor. A boost converter is highly efficient; they can reach efficiency levels of up to 90% [38].

Principle of Operation

The main principle of a boost converter is the current in the inductor controlled by the fast-switching operation. Therefore, when the switch is closed in position 1, Figure 23 (a), the current flows through the inductor in the clockwise direction and the inductor stores the energy by generating a magnetic field.

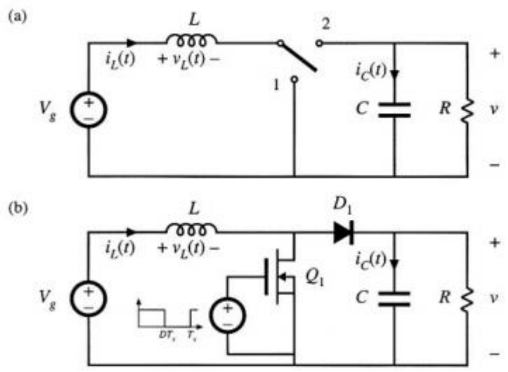

FIGURE 23: BOOST CONVERTER CIRCUIT - SWITCH IN POSITION 1 (A) & SWITCH IN POSITION 2 (B) [40]

When the switch is open in position 2, Figure 23 (b), the current is reduced since the impedance will be higher. The magnetic field created earlier will be reduced in energy to maintain the current towards the load. The two sources will be in series, and this results in a higher voltage to charge the capacitor through the diode like in Figure 23 (a) [38].

Observing the operation of a boost converter in a practical realization of the switch, it would be using a transistor and a diode or two transistors for a more efficient converter. Using a small-ripple approximation together with the principles of inductor volt-second balance and capacitor charge balance applied can help to estimate the steady state output voltage and inductor current for a boost converter. If the switch is in the position 1, Figure 23(a), the right-hand side of the inductor is connected to ground, this means that the current flowing through the inductor is in a clockwise direction. The inductor stores the energy by generating a magnetic field. The polarity of the left side of the inductor is positive.

$$v_L = V_g$$

EQUATION 15: INDUCTOR VOLTAGE

$$i_c = -\frac{v}{R}$$

EQUATION 16: CAPACITOR CURRENT

If the switch is in position 2, Figure 23 (a), the voltage drops across the load which is why the current is reduced. Thus, the magnetic field created in position 1 will be converted back to energy to maintain current towards the load. The polarity of the left side will now be negative, resulting in the two sources in series causing a higher voltage to charge the capacitor though the diode. The inductor voltage and capacitor current can now be represented as:

$$v_L = V_g - v$$

EQUATION 17: INDUCTOR VOLTAGE

$$i_c = i_L - \frac{v}{R}$$

EQUATION 18: CAPACITOR CURRENT

Applying the small-ripple approximation, **v ≈ V** and **i_l ≈ I**, which gives:

$$v_L = V_g - V$$

EQUATION 19: INDUCTOR VOLTAGE WITH SMALL- RIPPLE APPROXIMATION

$$i_c = I - \frac{V}{R}$$

EQUATION 20: CAPACITOR CURRENT WITH SMALL- RIPPLE APPROXIMATION

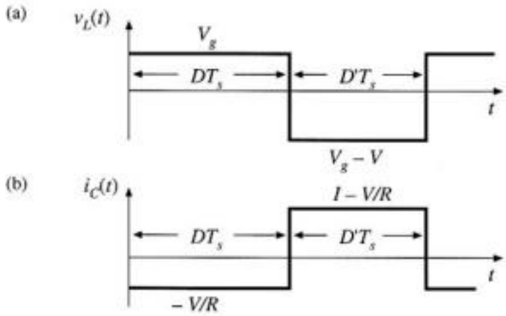

FIGURE 24: BOOST CONVERTER VOLTAGE AND CURRENT WAVEFORMS [41]

Referring to the waveform in Figure 24, the DC output voltage of the converter is greater than the input voltage $\mathbf{V_g}$. The subinterval, $\mathbf{v_L(t)}$ is equal to the input voltage $\mathbf{V_g}$. A positive volt-seconds is applied to the inductor. The volt-seconds applied over one switching period must be equal to zero as it is in steady-state. During the second subinterval negative volt-seconds must be applied. This means that the inductor voltage during the second subinterval ($\mathbf{V_g - V}$), is zero. As a result, this value is greater than $\mathbf{V_g}$.

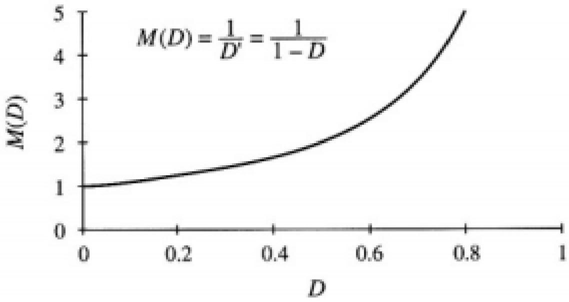

FIGURE 25: CONVERSION RATIO OF BOOST CONVERTER [40]

The ratio of the output to the input voltage of a DC-DC converter is the voltage conversion ratio M(D).

$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1-D}$$

EQUATION 21: CONVERSION RATIO FORMULA

Equation 21, suggests that the output voltage becomes larger as duty cycle is increased from the range of 0 to 1. The output voltage can be amplified within a certain range by controlling the switching duty cycle. Theoretically, the inductor current would go to infinity when the cycle is getting close to 1. Non-linearity will be present caused by the large current. This is due to the inductor resistance and semiconductor forward voltage. The output voltage would drop greatly, and power losses will increase due to the non-ideal components.

The inductor current, $\boldsymbol{i_L}$, waveform and its ripple, $\Delta \boldsymbol{i_L}$. When looking at the switch while it is off, the slope of the inductor current is given by:

$$\frac{d_i(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g}{L}$$

EQUATION 22: SLOPE OF INDUCTOR CURRENT

When the switch is on, the slope of the inductor waveform is:

$$\frac{d_i(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g - V}{L}$$

EQUATION 23: SLOPE OF INDUCTOR WAVEFORM

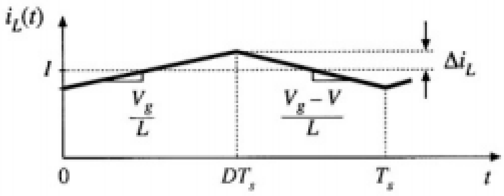

FIGURE 26: BOOST CONVERTER INDUCTOR CURRENT WAVEFORM [40]

The solution for the inductor current ripple through the inductor is:

$$\Delta \boldsymbol{i_L} = \frac{V_g}{2L} DT_s$$

EQUATION 24: INDUCTOR RIPPLE CURRENT

Equation 24 can be used to select a value L if a given value of Δi_L is obtained.

Similarly, the capacitor voltage $v(t)$ waveform can be sketched, and an expression can be derived for the output voltage ripple peak magnitude Δv . During the first subinterval, the capacitor voltage slope from the waveform $v(t)$ is

$$\frac{dv_c(t)}{dt} = \frac{i_c(t)}{C} = \frac{-V}{RC}$$

EQUATION 25 : FIRST SUBINTERVAL SLOPE

During the second subinterval, the slope is:

$$\frac{dv_c(t)}{dt} = \frac{i_c(t)}{C} = \frac{I}{C} - \frac{V}{RC}$$

EQUATION 26: SECOND SUBINTERVAL SLOPE

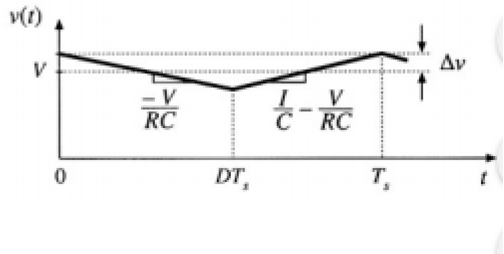

FIGURE 27: BOOST CAPACITOR VOLTAGE WAVEFORM [40]

The formula for the output voltage ripple is represented as below, considering both subintervals it is represented as follows:

$$\Delta v = \frac{V}{2RC}\, DT_s$$

EQUATION 27: OUTPUT VOLTAGE RIPPLE

Using this expression, the capacitor value ***C*** can be selected which then gives an output voltage ripple peak magnitude $\boldsymbol{\Delta v}$. For greater values, the output ripple peak magnitude is reduced accordingly [38].

4.2 Inverters

The inverter is an electrical device that converts a DC input into a symmetric AC output [42]. The ideal output can be represented in a sinusoidal waveform or a non-sinusoidal waveform. The inverter is a Voltage source inverter and if the input is a current then it can be called a current source inverter. There are two types of loads used in inverters, which is single phase and three-phase inverters. For this report we are going to be mainly focused on a full bridge and single-phase inverter.

Single Phase Full Bridge Inverter

A full bridge single phase inverter is a switching device that generates a square wave AC output voltage on the application of DC input by adjusting the switch turning ON and OFF based on the appropriate switching sequence, where the output voltage generated is of the form +Vdc, -Vdc, Or 0 [43]

The inverter consists of four switches. When switch one and switch two are triggered simultaneously switch 3 and four are too. This type of inverter can output twice the power than a half-bridge inverter with the same input voltage.

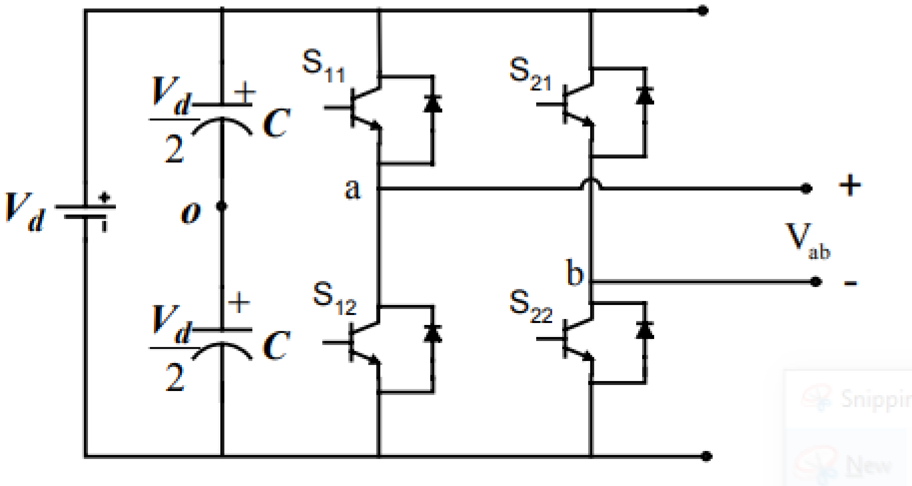

FIGURE 28: *FULL BRIDGE INVERTER*

$$\frac{v_d}{2}(s_{11} - s_{12}) = V_{an} + V_{no} = V_{ao}$$

$$\frac{v_d}{2}(s_{21} - s_{12}) = V_{bn} + V_{no} = V_{bo}$$

$$V_{ab} = V_{an} + V_{bn}$$

Output voltages, V_{an} and V_{bn} are from phase A and B to an arbitrary point **n**. The neutral voltage between point **n** and the mid-point of the DC source is source. Using Fourier series can be used to approximate the switching function of the device. This is represented as $\frac{1}{2}(1+M)$, where M is the modulation signal which compared to the triangular waveform yields the switching pluses. So, then the modulation signals can be obtained as:

$$M_{11} = \frac{2(V_{an} + V_{no})}{V_d}$$
$$M_{21} = \frac{2(V_{bn} + V_{no})}{V_d}$$

Above equation gives the expression for the modulation signals for the signal phase dc-- ac conversion inverter [44].

The Advantages of using a full bridge inverter is that it has an absence of voltage fluctuations in the circuit, it is suitable for high voltage, it is energy efficient and the current rating of the power devices is equal to the load current. The efficiency of a full-bridge inverter is more than the half bridge inverter.

4.3 Pulse Width Modulation

Pulse width modulation (PWM) has many different uses that allows us for controlling different electrical devices, such as LED's and motors. PWM's are also found in step up or step-down power supplies, which can be seen in our boost converter in 4.2.2 Boost Converter Analysis which varies the perceived power going to the electronic device, by very quickly turning the power ON and OFF.

The perceived output is changed by varying the duty cycle, which is the percentage of time the signal is turned on versus it being off. This means that with a 50% Duty Cycle the signal is on (current is flowing) half of the time and not on (not flowing) the other half.

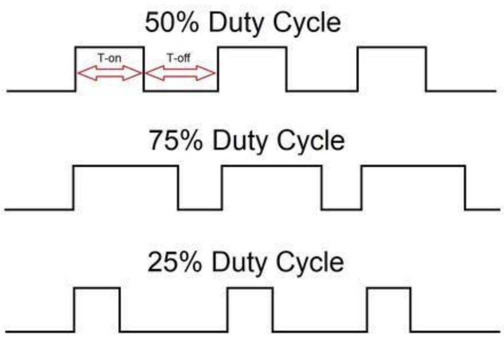

FIGURE 29: DUTY CYCLE

Pulse width modulation is much more efficient than the typical DC voltage controller, where they would use resistance to lower the voltage, that would mean any power not needed would be wasted through heat. A sinusoidal pulse width modulation (SPWM) is used to control our inverter. A sine wave voltage is primarily an analogy voltage which alters its magnitude over time, and we can reproduce this behaviour of a sine wave by continually changing the duty cycle of the PWM wave. The SPWM increasing and decreasing the duty cycle of the pulse wave can be seen in the figure below.

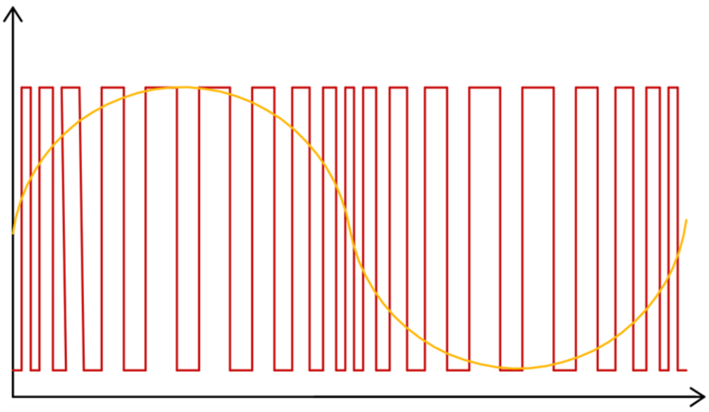

FIGURE 30: CHANGING DUTY CYCLE OF PWM [45]

If you look at the schematic of the inverter, the capacitor connected at the output is for smoothing the ac signal from the carrier frequency. The duty cycle will start very small for example at 1% charging the capacitor a small bit, then 5% duty cycle charge the capacitor a bit more and so on until the signal has reached a duty cycle of 100% where it goes back down to 1%. This will create a very smooth curve like a sine wave at the output. So, by providing proper values of the duty cycle at the input, we will have a very smooth sinusoidal wave at the output [45].

The voltage across the inverter's load when using SPWM control is given by:

$$\boldsymbol{V_o = mV_{DC}\sin(\omega t)}$$

EQUATION 28: SPWM INVERTER OUTPUT VOLTAGE [46]

Where m is the modulation index of the PWM controller and $\boldsymbol{V_{DC}}$ is the DC input voltage to the inverter. $\boldsymbol{m}$ is given by:

$$m = \frac{V_{ref}}{V_c}$$

EQUATION 29: MODULATION INDEX

Where V_{ref} is the peak amplitude of the reference voltage signal and V_c is the peak amplitude of the carrier voltage signal.

The derivation of Equation 28 and Equation 29 is beyond the scope of this module and so is not included in this report.

5. Circuit Design, Implementation and Analysis

The hydroelectric power circuit design will seem very impractical based on the application the circuit is being built for, the number of parameters and theoretical values that need to be considered can be quite tedious to calculate.

The goal we had in mind for this project was to generate enough power from our hydroelectric system to power a water heater in an average American home, with a single phase, 120V_{rms} power supply. We have seen that much of the power consumed in a US house was on heating water. About 20% of power consumption in US homes in the year 2015 was used for just heating water [47]. This is a large portion of their electricity bill. Water heaters can range between 1kW and 4kW of power [48], so our goal was to achieve about 3kW from our system. Hopefully with our system being implemented into a home we can help reduce the electricity cost for heating water.

The impact of COVID-19 pandemic has also made hardware implementations very difficult to pursue, therefore the focus of the circuit design, implementation and analysis will be based on the simulation for this model. This section will examine the three main individual phases of the system and then create a final circuit which will encompass all three phases together using simulation.

5.1 Simulation using LTSpice

5.1.1 Rectifier Implementation

The rectifier is the introductory stage in the circuit. The voltage input we would receive from the generator would be AC, therefore it would be a very important process to convert AC to DC. As mentioned in 3. Rectification, it would be beneficial to implement a full wave rectifier rather than a half wave. As a larger current would be amplified, full-wave rectification is much more appropriate in the simulation due to its performance characteristic. The team has taken into consideration of using ideal conditions for the rectifier implementation, this will allow the rectifier phase of the system to achieve the best results possible.

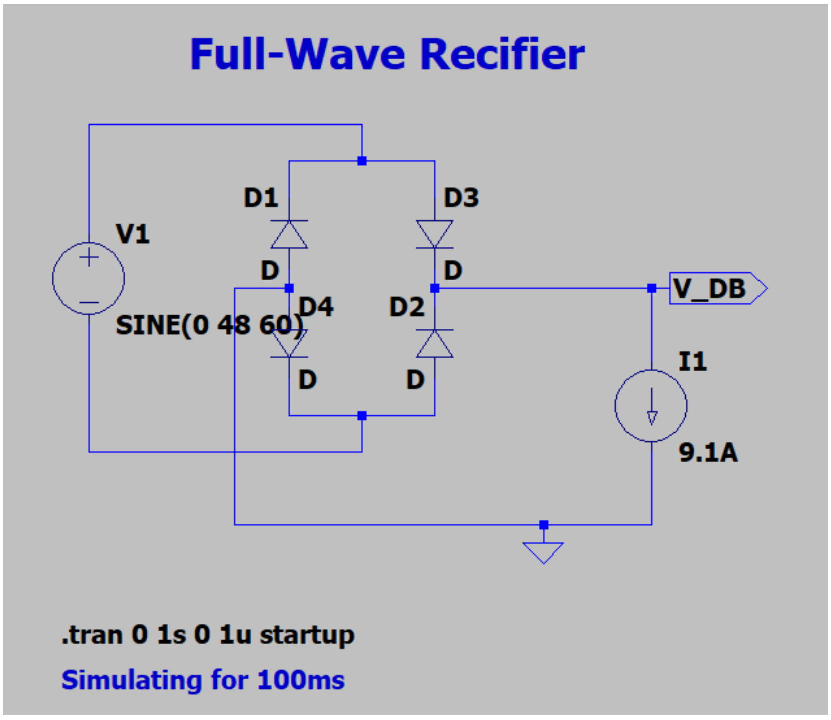

FIGURE 31 - FULL WAVE RECTIFIER WITHOUT A FILTER

From Figure 31, the rectifier schematic is built with a current source in place instead of a resistive load. The comparison graph will give the team a good idea of what the peak voltage and root mean squared of the rectified voltage will be for further analysis.

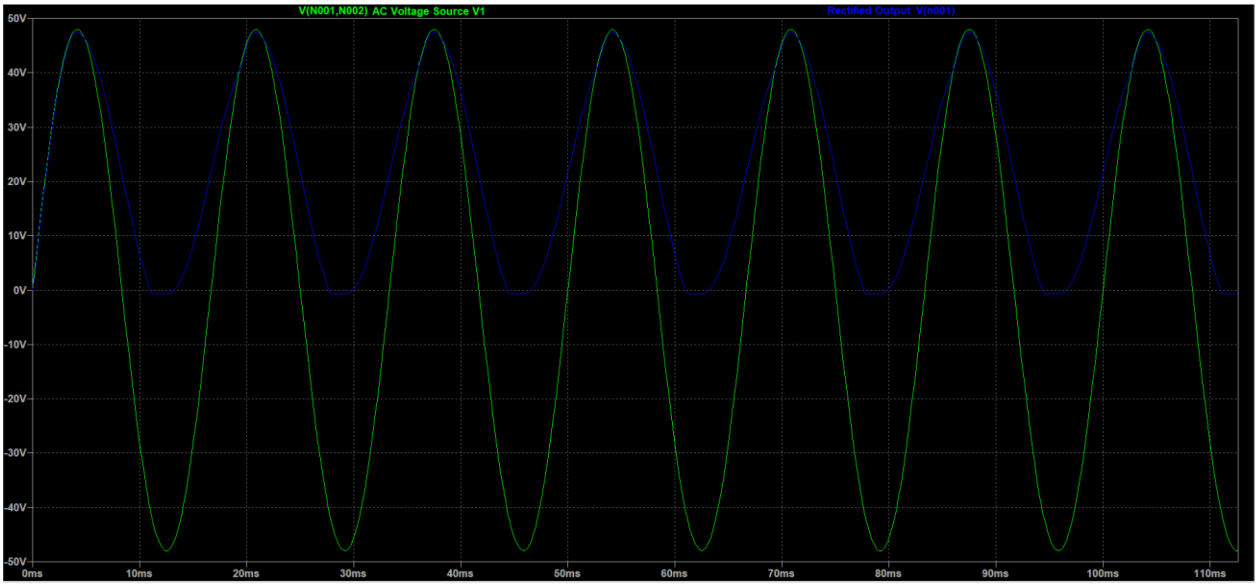

FIGURE 32 - VOLTAGE COMPARISON BETWEEN DC AND AC

After simulating for circuit for 110ms, the results are plotted in the graph in Figure 32. Where the AC voltage is plotted against the rectified voltage. The rectified voltage has many ripples which is not ideal for a DC voltage, since rectification means to transfer AC voltage to DC voltage, it is important that ripples are filtered out making the DC voltage much smoother. As mentioned in 3.3 Smoothing Capacitor Ripple Voltage, the capacitor acts as a filter to these ripples and dissipates them from the waveform.

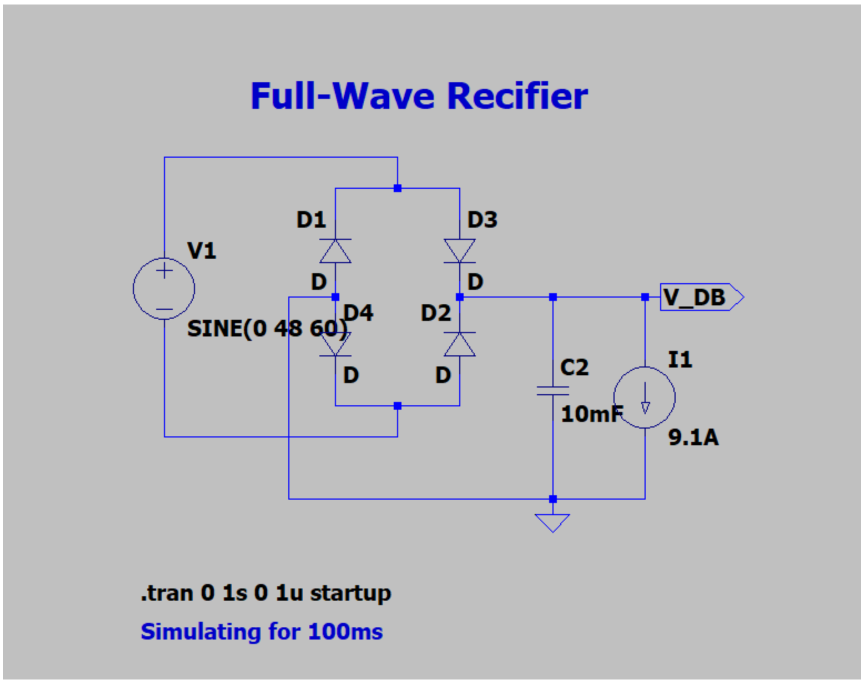

FIGURE 33 - FULL WAVE RECTIFIER WITH A FILTER

From Figure 33, the rectifier was built with a 10mF capacitor put in. When the circuit was simulated, the rectified voltage response received was different as expected. The graph can be seen in Figure 34.

FIGURE 34 - VOLTAGE COMPARISON GRAPH WITH CAPACITOR SMOOTHING (10MF)

Due to capacitor smoothing, the rectified DC voltage is looking much better with minimal ripple. The DC voltage was hovering around 41V – 47V approximately. The team also wanted to experiment what the rectified voltage would look like if the capacitance was increased. Our findings for increasing the capacitance can be seen in Figure 1Figure 35.

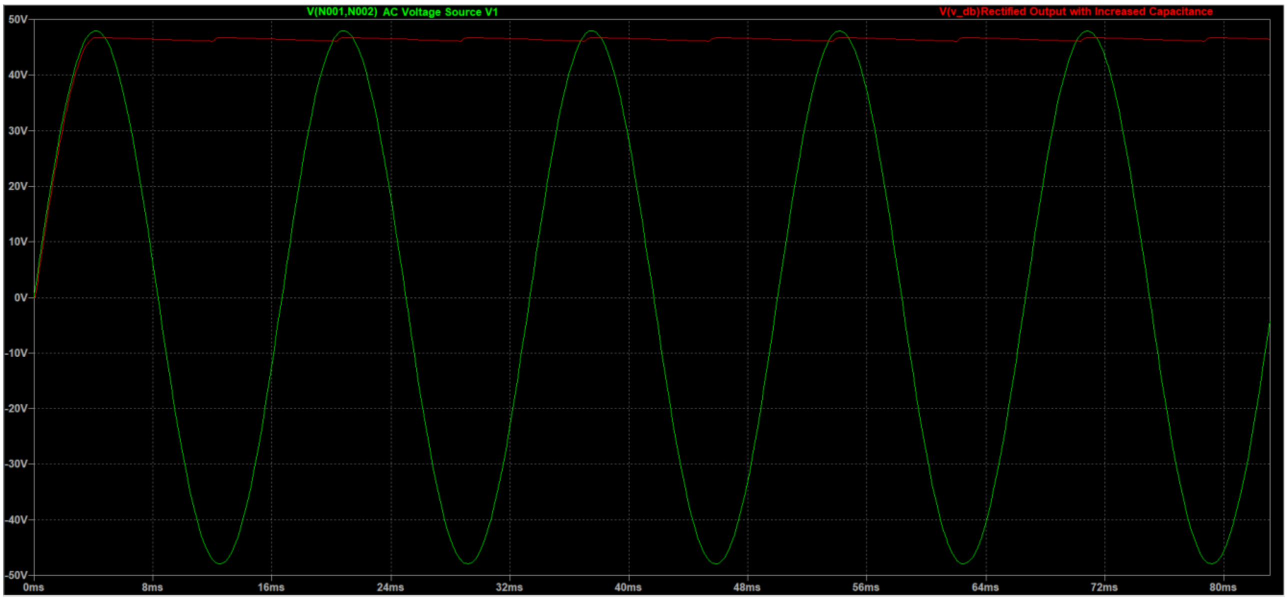

FIGURE 35 - VOLTAGE COMPARISON GRAPH WITH CAPACITOR SMOOTHING (100MF)

The new capacitance chosen was 100uF and from our reported findings, the group could confirm that increasing the capacitance will have a better smoothing effect, making the DC voltage to be much more precise and steadier. Measuring the DC output of a full wave rectifier can be very important. Equation 8 can be used measuring the DC output (no-load) for a sinusoidal input voltage.

5.1.2 Boost Converter Implementation

The boost converter is the middle stage in the circuit and the important aspect of this circuit depends on the focus of the application. The target application for this project would be used to for a water heater at home. This application would require the voltage to be stepped up since the generator voltage will not be sufficient to power the water heater. The boost converter will step the voltage to a desired value; therefore, it would be a very important process to convert DC to DC. As mentioned in 4.2.2 Boost Converter Analysis, it would be beneficial to implement a boost converter if the voltage required needs be stepped up. This is the appropriate selection for our circuit simulation.

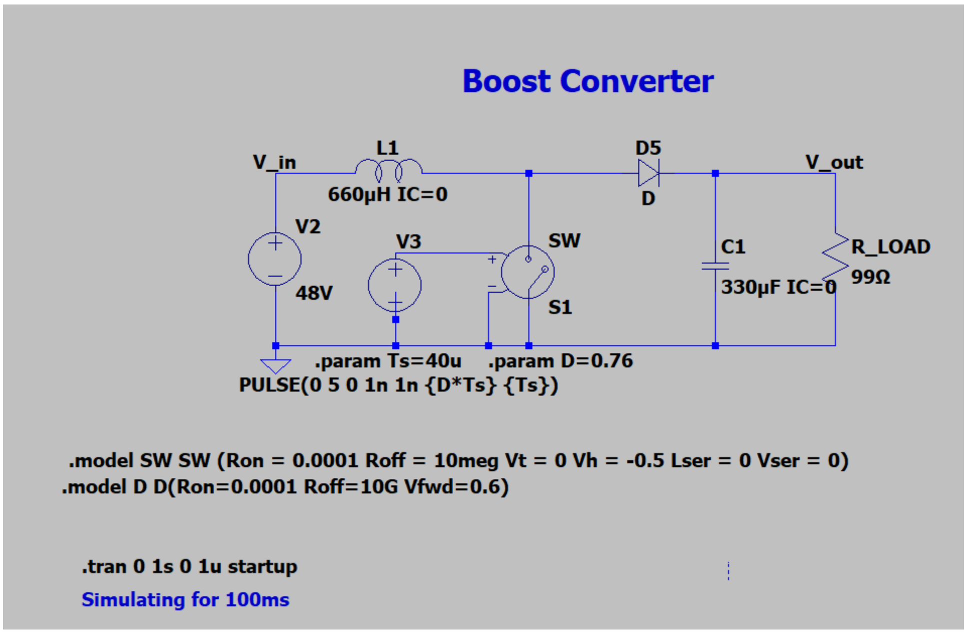

FIGURE 36 - FULL BOOST CONVERTER

From Figure 36, the boost converter schematic is built with a straight DC voltage source at 48V (as previously seen from the rectifier) and an ideal switch in place so that our boost converter implementation inhibits ideal characteristics. The circuit also contains a resistive load which is kept in place for analysing the output voltage.

The boost converter contains a switch which is denoted by S1 in Figure 36. When the switch is on (T=Ton) the circuit will close, and the supply voltage will start to charge the inductor L1. In this case the output voltage will result to be 0 because with S1 on, this will result in a short circuit. When S1 is off (T = Toff), the inductor will reverse its polarity and the charge stored in the inductor will be released. The inductor L1 is kept in the boost converter as a means of stepping up the voltage. The voltage across an inductor is dependent on the inductance and the rate at which the current is changing with respect to time. (ref equation) mathematically describes this principle where $\boldsymbol{L}$ is the inductance, $\boldsymbol{i}$ is the current.

$$V_{inductor} = L\frac{di}{dt}$$

EQUATION 30: CONVERTER INDUCTOR VOLTAGE

The voltage in the schematic was chosen to be 660µH which is the most accurate value to reach the expected output voltage, in the case of the boost converter, the output should be approximately 200V
When S1 is closed in this case the output voltage will be the result of be Equation 31.

$$V_{out} = V_{inductor} + V_{in}$$

EQUATION 31: CONVERTER OUTPUT VOLTAGE

The switching period determines how much ripple there will be in the output voltage waveform. The higher the switching period, the larger the ripple in the output voltage. Generally, the maximum period you should consider is 100µs, however this still produced an unsatisfactory amount of ripple. The period was reduced from that point until we were satisfied with the amount of ripple.
The ON time of the switching signal determines the voltage amplitude of the output. It is determined by the duty cycle and the switching period. The duty cycle can be found using Equation 32.

$$D = 1 - \frac{V_{in}}{V_{out}}$$

EQUATION 32: CONVERTER DUTY CYCLE

In this case, the duty cycle was found to be 0.76, which meant an ON time of 30.4µs.

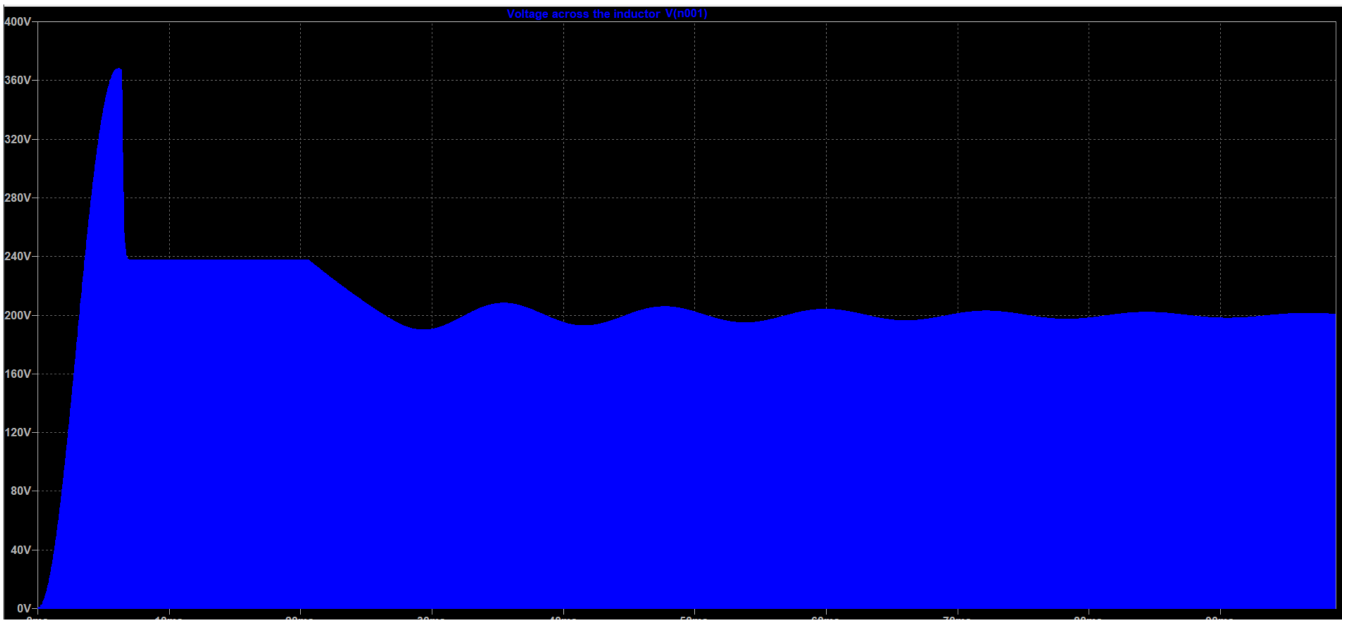

FIGURE 37 - VOLTAGE ACROSS THE INDUCTOR

The simulation ran for 100ms and voltage across the inductor was to be analysed first. Figure 37 shows the voltage output and from the findings, there is an increasing amount of disturbance and noise which appears in the output. This is to be expected as the voltage has not reached the capacitor yet to bring the voltage to the load and to make the output much smoother. When analysing the output, there will momentarily be a sharp spike in the voltage which indicates that the switching takes places very fast in the initial state.

FIGURE 38 - BOOST CONVERTER OUTPUT

When the output is analysed across the resistive load, the large voltage spike due to the rapid switching of S1 still exists which is seen Figure 38. The difference in this graph is that the output voltage approaches steady state throughout time. From the graph, the steady state voltage comes out to be approximately 200V, this turned out to be our expected value.

5.1.3 Inverter Implementation

The inverter is the final stage of the circuit and is responsible for turning the DC input from the boost converter into an AC signal with desired frequency and amplitude. It does this using a single phase, full-bridge inverter, whose switches are controlled by a PWM signal, that is connected to an LC filter. From our desired application, our desired output voltage is $120V_{rms}$ at 60Hz and our desired power output is 3kW.

To start, we need to build our PWM module that will control the switches of the inverter. The reference signal will have the same frequency as our desired voltage output, but to find its amplitude we use Equation 31:

$$\boldsymbol{V_{o(rms)} = 120V \qquad V_{o(pk)} = \sqrt{2}V_{o(rms)} = 169.71V}$$

$$\boldsymbol{V_{o(pk)} = \frac{V_{ref}}{V_c} V_{DC}}$$

EQUATION 33: PEAK INVERTER VOLTAGE OUTPUT

We arbitrarily set $\boldsymbol{V_c}$ to 5V since its value has no effect other than determining the value of $\boldsymbol{V_{ref}}$ to achieve the necessary modulation index. Substituting values into Equation 29 gives us:

$$\boldsymbol{169.71 = \frac{V_{ref}}{5}(200)}$$

$$\boldsymbol{V_{ref} \approx 4.24}$$

The last parameter of the PWM is the frequency f_c of the carrier signal. This parameter is also somewhat arbitrary, however if the frequency is too low, the switches of the inverter will not trigger fast enough to produce a waveform matching the reference waveform. Alternatively, the frequency of the carrier signal can be high enough to produce a waveform matching the reference but with large amounts of ripple.

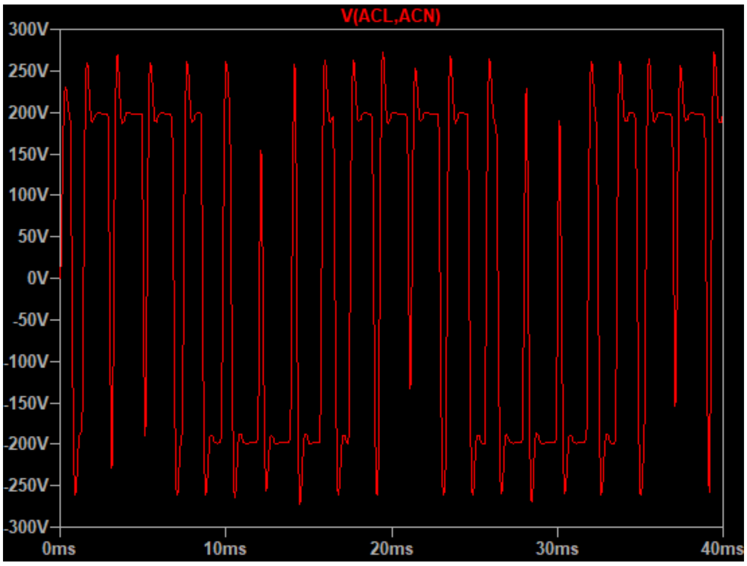

FIGURE 39 - VO WHEN FC=500HZ

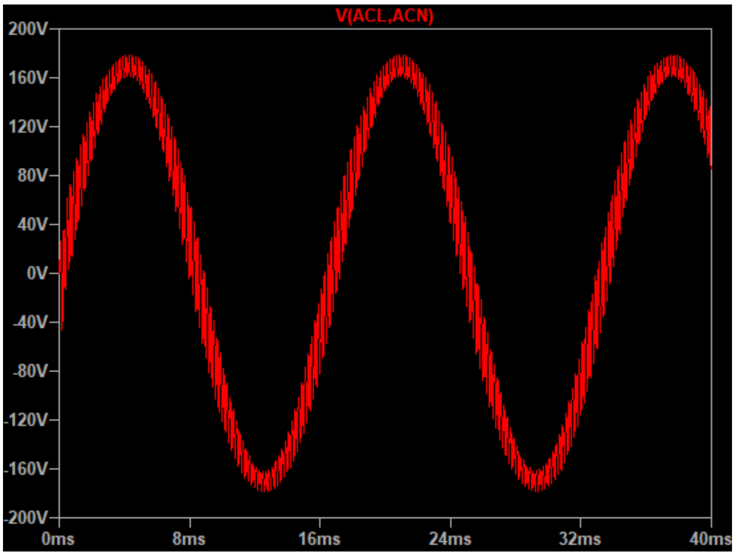

FIGURE 40 - VO WHEN FC=5000HZ

We chose $f_c = 66666.\dot{6}Hz$ as this provided a waveform that was accurate to the reference and had a small amount of ripple.

The final component of a PWM controller would be a comparator, however since we are only simulating the circuit with ideal components, we used conditional voltage sources. These will output the signals that trigger the switches based on a comparison between the carrier and the reference signals.

Voltage source B1 is programmed to output 2V when the voltage of the reference signal is greater than or equal to the voltage of the carrier signal and 0 otherwise. Voltage source B2 is programmed to output 2V when the voltage of the reference signal is less than the voltage of the carrier signal and 0 otherwise. They control switches 2 & 5 and 3 & 4 respectively.

Figure 41 is the implementation of the above process:

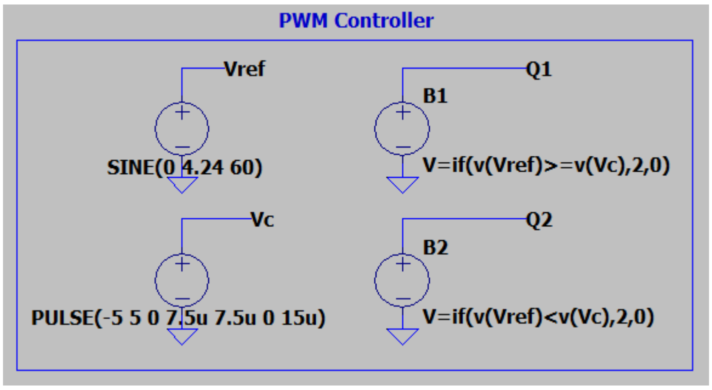

FIGURE 41 - PWM CONTROLLER

The inverter circuit itself does not have any components with specific parameters. We assume the DC voltage input from the converter is ideal and then arrange the switches and diodes as standard.

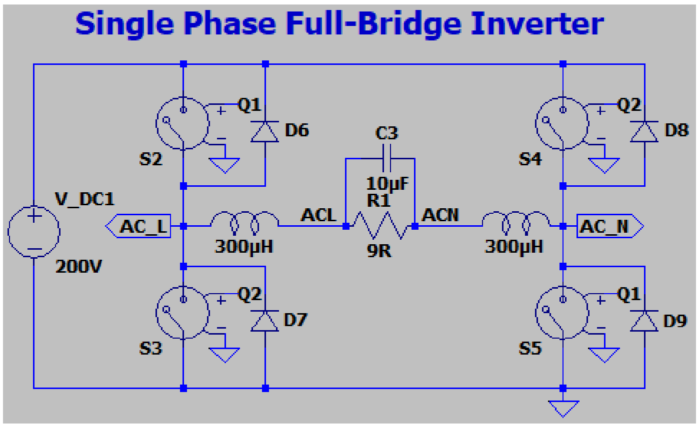

FIGURE 42 - INVERTER SIMULATION

The value of the resistor determines the power output of the inverter. This is because the lower the resistance is, the more current can flow. We can determine its value using our desired peak voltage and power outputs.

$$p = iv \qquad \frac{v}{r} = i$$

$$r = \frac{v^2}{p} = \frac{169.71^2}{3000} = 9.6\Omega \sim 9\Omega$$

EQUATION 34: INVERTER LOAD RESISTANCE

Choosing the values of the inductor and capacitor are somewhat arbitrary but there are some guidelines to be followed (note that two inductors are used in the circuit to preserve symmetry, they act as a single inductor with the inductance of the two inductors combined).

The reason we need an inductor is to make the output waveform sinusoidal. The inductor achieves this by charging and discharging every time the voltage changes polarity (every time the switches change state). Without an inductor, the output voltage would be a square wave with varying pulse widths. The reason we need a capacitor is to reduce the ripple effect in the sinusoidal waveform.

There are infinite combinations of inductance and capacitance that will give you the filter response you require, so normally a capacitance is chosen and then the appropriate inductance is worked out using various methods. We decided to set the capacitance to 10µF and then choose an inductance that would produce a LC filter with a cut-off frequency at the logarithmic half-point between 60Hz (our desired output frequency) and 66,666.67Hz (frequency of the PWM carrier signal). We can then use the equation of an LC lowpass filter to find the appropriate value for the inductor.

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

EQUATION 35: CUT-OFF FREQUENCY OF LC LOWPASS FILTER

f_0 is given by:

$$f_0 = \sqrt{60 \times 66666.\dot{6}} = 2000Hz$$

The result of this process was an inductor with an inductance of 633.26µH. We chose to use an inductance of 600µH because it was easier to implement with our symmetric inductors.

The output waveforms of the entire inverter system can be seen from Figure 43.

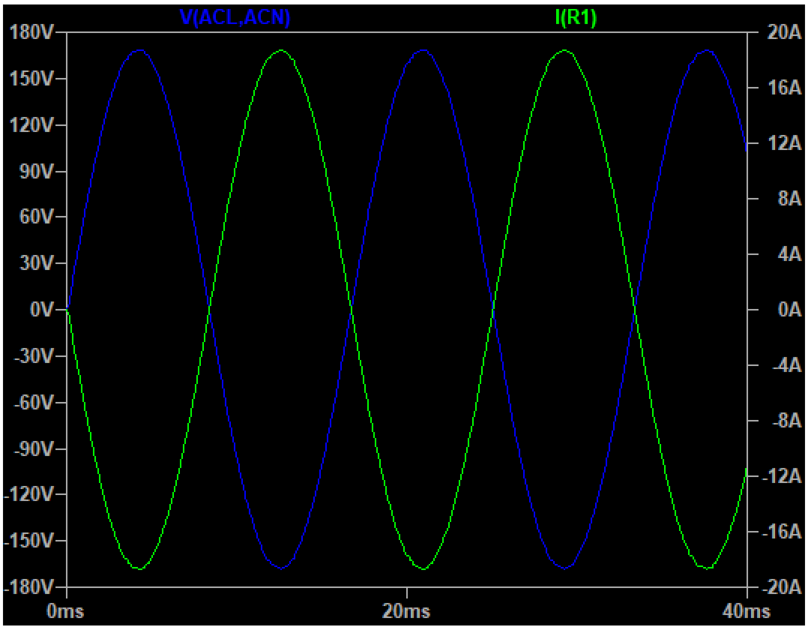

FIGURE 43 - VOLTAGE AND CURRENT ACROSS THE RESISTOR

5.1.4 Final Circuit Implementation

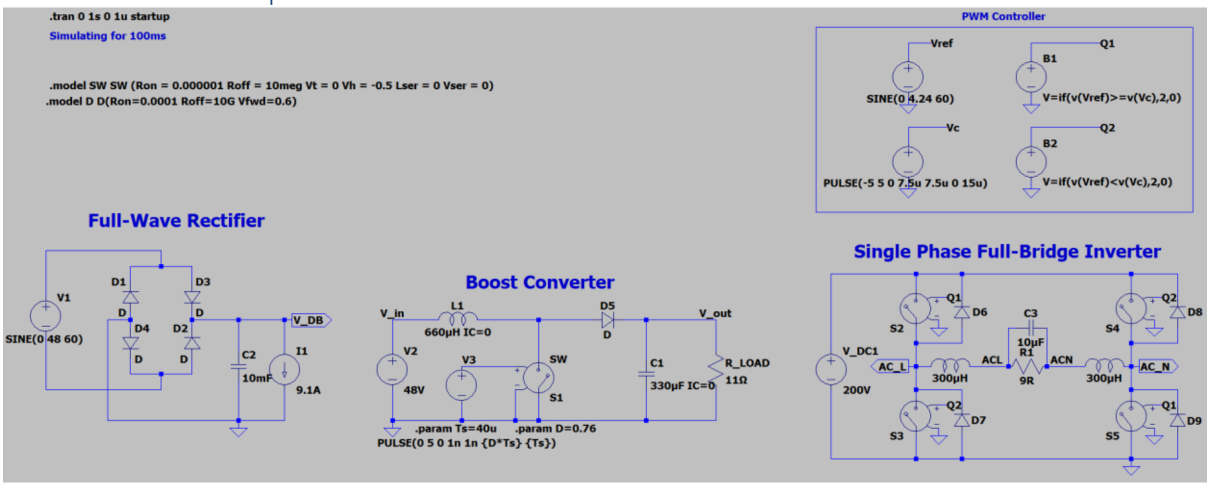

FIGURE 44 - FINAL CIRCUIT IMPLEMENTATION

Figure 44 shows all the previously described components of our circuit combined into one simulation. For the sake of simplicity, each segment is isolated from the others.

If they were to be wired together, the output waveform would lose its quality. This is because, no matter how well you design and build these circuits, they do not perform their tasks perfectly; the output voltage of a rectifier will always have ripple, the output voltage of a boost converter will always oscillate around its steady-state and an inverter will never produce a sine wave without ripple. All the imperfections and errors introduced to the system by its components increases the complexity of the calculations required to determine component parameters and makes it more difficult to troubleshoot.

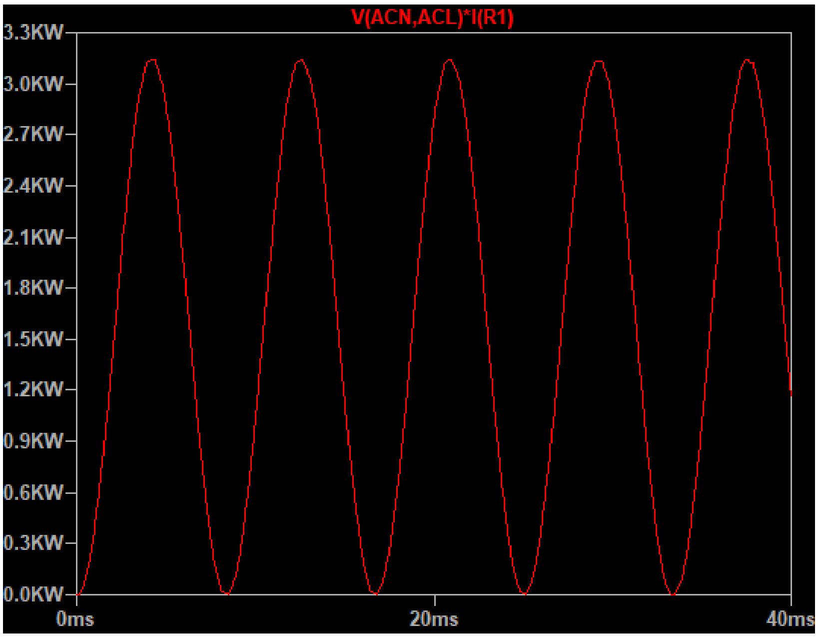

FIGURE 45 - POWER DISSIPATED IN THE RESISTOR

The final output to look at would be the power dissipated in the resistor in the final circuit implementation. The expected power is approximately just under 3.3KW and from Figure 45, this seems to be the case for the output power. This amount of power will be enough to power a water heater appliance in a home which tended to be our target application. Due to time constraints and project deadlines, further testing of the system could not be completed. There were more opportunities to test the efficiency of the system by producing more graphs and analysing the findings. The overall result of the voltage and power is more than enough to complete the simulation and to remark it as a success.

6. Summary and Conclusion

Throughout the first semester, we conceived of an application for a hydroelectric power-generating system on a pico-scale. Although much physical testing could not be done, the system in hardware would have been very difficult to develop therefore the team successfully managed to simulate a circuit to convert the output of a theoretical generator into useable electricity using ideal components. As future work, the next goal of this project would be to swap these ideal components and replace them with real components, this may lead to further research as our ideal output may change. Thus, for now, we fulfilled our research topic of converting energy from a renewable source into usable electricity. A greater understanding of power electronics was developed, and the limitations of rectifiers, converters and inverters was experienced first-hand.

The logistics of the project were well thought-out, making progress smooth and even with everyone doing the same amount of work consistently across the entirety of the process. Work packages were delegated when necessary and communication between all members was positive and constructive. The work packages for the project are in Appendix B – Gantt Chart & Work Packages. Weekly meetings ensured that the schedule was being followed and each person knew the tasks that every other member was completing. The agendas and minutes realize the team's communication with each other and with the project facilitators as seen in Appendix A – Agendas & Minutes.

6.1 Future work

The obvious next step in our simulation would be to connect each segment of the circuit and reconfigure the parameters to produce our desired output and from there we could replace ideal components with real ones. After that, we would likely have to implement control methods in our circuitry to allow for a varying voltage input from the turbine (like we would get in practice) as well as a varying output load resistance. Gradually, we would improve our simulation until it was ready to be tested in real life, using real components.

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Appendix A – Agendas & Minutes

MEETING 1

Location:	Teams
Date:	6th October 2020
Time:	5PM – 5:30PM
Facilitator:	Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Individual drafts on research conducted.
5:10 – 5:20	Research being conducted up to date. Group planning on what aspects to tackle.
5:20 – 5:30	Discuss next steps taken to draft up the interim report.

Action Items	Owner(s)	Deadline
Research assigned topics and write up the drafts.	All	12/10
Research history.	Samson	12/10
Research specifics of pico/micro hydro.	Ruari	12/10
Research statistics.	Vinayak	12/10
Get into contact with hydro worker.	Sruthi	12/10

MEETING 2

Location: Teams

Date: 13th October 2020

Time: 5PM – 5:30PM

Facilitator: Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Discussion on the real-life application of the project (efficiency and limitations).
5:10 – 5:20	Discussion on simulating the system.
5:20 – 5:30	Discussion on contents of Rytis' report.

Action Items	Owner(s)	Deadline
Move focus from generator itself to the processes after it.	All	None
Decide on what the system should be powering.	All	15/10
Make use of the IEEE website.	All	None

MEETING 3

Location:	Teams
Date:	23rd October 2020
Time:	5PM – 5:30PM
Facilitator:	Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Discussion on the research question.
5:10 – 5:20	Discussion on topics for research.
5:20 – 5:30	Discussion on contents of Rytis' report.

Action Items	Owner(s)	Deadline
Decided on an application and research question.	All	None
Research overall system efficiency, environmental impact and methods of hydro generation.	Ruari	3/11
Research and write up boost converters.	Sruthi	3/11
Research and write up rectifiers and buck converters.	Vinayak	3/11
Research and write up generators and transformers.	Sean	3/11
Research and write up advantages and limitations.	Samson	3/11

MEETINGS 4 & 5

Location: Teams

Date: 26^{th} October & 3^{rd} November 2020

Time: 5PM – 5:30PM

Facilitator: Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30 Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.

5:00 – 5:10 Confusion on project requirements and application.

5:10 – 5:20 Discussion on topics to be included in report.

5:20 – 5:30 Discussion on components to be simulated.

Action Items	Owner(s)	Deadline
Pick a suitable generator for application, do not need to simulate it.	All	None
Simulation should include a full wave rectifier, DC-DC converter and a full bridge inverter.	All	None
Only efficiency of circuitry matters, generator efficiency need only be mentioned.	All	None

MEETING 6

Location: Teams

Date: 9th November 2020

Time: 5PM – 5:30PM

Facilitator: Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Literature report feedback.
5:10 – 5:20	Discussion on application.
5:20 – 5:30	Discussion on simulation components.

Action Items	Owner(s)	Deadline
Application chosen to be a pump storage system for a building.	All	None
Research turbine outputs.	Ruari	15/11
Build converter circuit in LTspice.	Vinayak	15/11
Modify report based on feedback.	Sean	15/11
Build inverter circuit in LTspice.	Sruthi & Samson	15/11

MEETING 7

Location: Teams

Date: 15th November 2020

Time: 5PM – 5:30PM

Facilitator: Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Literature report feedback from Rytis.
5:10 – 5:20	Discussion on simulation.
5:20 – 5:30	Discussion on final report.

Action Items	Owner(s)	Deadline
Continue work from previous week with Rytis' advice in mind.	All	23/11

MEETING 7

Location:	Teams
Date:	23rd November 2020
Time:	5PM – 5:30PM
Facilitator:	Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
5:00 – 5:10	Discussion about relevance of literature report in final report.
5:10 – 5:20	Discussion on content to be added to final report.
5:20 – 5:30	Discussion on final report.

Action Items	Owner(s)	Deadline
Create basis of final report.	Vinayak	14/12
Design and write up inverter.	Sruthi & Samson	14/12
Application write up.	Ruari	14/12
Modify transformers and turbines write up to be more relevant.	Sean	14/12

MEETING 8

Location: Teams

Date: 14th December 2020

Time: 5PM – 5:30PM

Facilitator: Bob Lawlor

Members attending: Vinayak Unnithan, Ruari Wall, Sean O'Leary, Sruthi Jose, Samson Adeptite

Absences: None

Agenda Items

5:00 – 5:30	Overview: General discussion on the progress made so far and to discuss to Bob our clear idea and the methods taken to get the project going.
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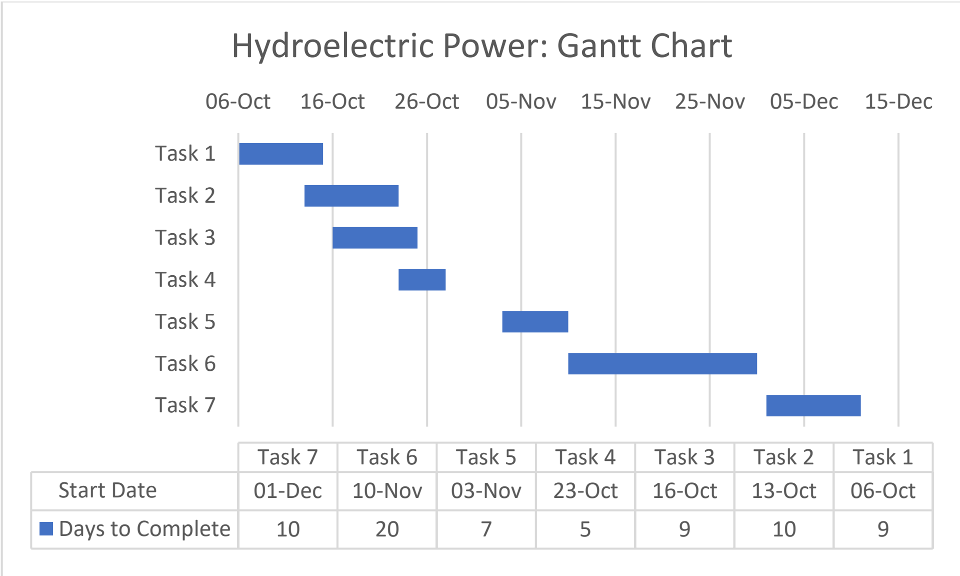
5:00 – 5:10	Discussion on simulation provided by Rytis.
5:10 – 5:20	Discussion on group's simulation.
5:20 – 5:30	Discussion on write-ups yet to be completed.

Action Items	Owner(s)	Deadline
Modify simulated inverter segment based on Rytis' advice.	Ruari	21/12
Modify simulated converter segment based on Rytis' advice.	Vinayak	21/12
Complete remaining write-ups.	Sean, Sruthi & Samson	21/12

Appendix B – Gantt Chart & Work Packages



Task Activity
1: Preliminary Research into hydroelectricity
2: Further Research into specifics of hydropower (such as methodology, efficiency, impact, etc.)
3: Research into required circuitry components (such as converters, rectifiers, transformers, etc.)
4: Interim report write-up
5: Make corrections to interim report based on feedback
6: Implement and simulate system
7: Compile results and write up Final Report

Work package breakdown

This breakdown contains the key work packages included in Term 1 & 2 for EE313 Group 3 Hydroelectric Power Generation.

1.2 Brief analysis and project focus

The team reads the project guidelines to make sure the project focus resonates with them so that the project specifications required can be achieved.

1.3 Identifying research areas

The major areas for research are identified. These include hydroelectric power methods, Rectification and DC-DC Converters.

1.5 Literature report write-up

The team research existing literature such as the type of methodology used in past, current generation, and future. This will address the applications of the project focus and the ideas relating to their use.

1.6 Prepare consecutive draft write-ups

Upon receiving feedback from on the first draft, this can prepare the group for the first draft of the final report by keeping the necessary literature and expanding on system design, implementation, and analysis.

1.7 Finalising and submitting

Finalise the draft by ensuring the project facilitators read it and send feedback back to the group which ensures that the report is free of errors before submitting it.

Research topics

2. This section outlines the main research topics that were established in section 2 and section 3.

2.1 In-depth research of hydroelectric power history.

Includes numerous topics among the different types of methods such as inland methods and offshore methods. The working principle of hydroelectric power.

2.2 Rectification

These include fundamental techniques related to the hydroelectric power such as full wave rectifiers and capacitor smoothing.

2.3 Power conversion and Analysis

These include fundamental techniques related to the hydroelectric power such as buck converters, boost converters and inverters.

2.4 LTSpice Simulation and Analysis

2.4.1 Rectifier implementation

Designing a full wave rectifier on LTSpice to understand the fundamental functions of the circuit and relate that to our research and findings.

2.4.2Boost converter implementation

Designing a full boost converter with an ideal switch on LTSpice to understand the fundamental functions of the circuit and relate that to our research and findings.

2.4.3 Inverter implementation

Designing a full bridge inverter on LTSpice to understand the fundamental functions of the circuit and relate that to our research and findings.

2.4.4 Final circuit implementation

Designing a full hydroelectric power system on LTSpice by putting together the three main phases of the system to understand the fundamental functions of the circuit and relate that to our research and findings.

2.5 Final results

Analysing the output of the system in the final circuit implementation and checking the power dissipated over the resistive load to ensure the target power levels are satisfactory with the required power level.

Appendix C – Risk Assessment

Health and Safety Risk Assessment and Guidelines.

Every student group must perform a health and safety risk assessment of their project before commencing any work.

This should be done in consultation with their project supervisor. The Risk Assessment form must be assessed, along with any required material such as Material Safety Data Sheets and signed off by a member of the Health and Safety Committee.

The form is designed to identify any hazards that the proposed project might present to the students or people that may meet the project.

Issues to consider include

- **Hazardous materials, for example flammable materials, epoxies, cements, paints, aerosols, carcinogens, poisons, toxins…**
- **Working alone, at height, in confined space, in a dangerous area**
- **Working with electricity**
- **Working with machines and tools**
- **Working with biomaterials**
- **Working with heat or flame (e.g. soldering or hot air guns)**
- **Working with lasers**
- **Working with heavy or large items**
- **Working with fast spinning objects (e.g. fans or propellers)**
- **Disposable / Recycling of hazardous materials eg batteries, plastics, metal and those mentioned above.**

Where risks are identified, the students must discuss how the risk will be managed by listing what controls are in place and what further controls may be required.

The Risk Assessment Form should be included in your project report.

The Risk Assessment Form should be available for when requested by any staff member.

If this form is NOT available, then all work on the hardware aspects of your project MUST STOP until the form is signed off.

H&S committee members are: Mr. Andrew Meehan, Mr. John Maloco, Ms. Ann Dempsey, Prof. Ronan Farrell, and Dr Bryan Hennelly.

I confirm, I have no medical condition that impedes working on my Project, and I will advise a Health & Safety Officer if this status changes.

Signed: __ Vinayak Unnithan, Sean O'Leary, Sruthi Jose, Ruari Wall and Samson Adepitde.

____

PROJECT RISK ASSESSMENT FORM

NAME AND STUDENT NUMBER: Vinayak Unnithan - 18312811 Sean O'Leary - 17384786 Ruari Wall - 17394213 Sruthi Jose - 17303571 Samson Adeitde - 17370563	PROJECT NAME: Hydroelectric Power Generation
SUPERVISOR: Bob Lawlor	PROJECT LOCATION: Maynooth University

BRIEF DESCRIPTION OF PROJECT:
The purpose of this project is to fulfil several requirements set by the project guidelines in the EE313 Analogue Electronics 2 Module. The most important requirement is to design a system that generates power using a range of circuits for handling and manipulating analogue signals.

Hazards, Risk [High(H) Medium (M) Low (L)], and Control Measures

HAZARD	Risk	Controls
Risk of Electrical Shock	H	Wearing protective equipment such as rubber gloves
Risk of contracting COVID-19	M	Social Distancing and wearing masks

Identified risks should be discussed with your supervisor and a safe system of work agreed. A more in depth risk assessment may be required after initial review. Do not proceed until form is signed off.

WEEE Compliance & Recycling: Indicate below how you intend to mange and dispose of your projects material during and post project work.

Disposing of all paper used to write up notes into a recycling bin.

Further Controls Required

N/A

SIGNATURE OF STUDENT: Vinayak Unnithan, Sean O'Leary, Sruthi Jose, Ruari Wall and Samson Adeptide
___________________________ DATE: 23/12/2020

SIGNATURE OF SUPERVISOR: _________________________ DATE: _______________

DEPT HEALTH AND SAFTEY COMMITTEE MEMBER: _________________________ DATE: _______________