HARNESSING TIDAL ENERGY FOR POWER GENERATION IN SOUTH AFRICA

By

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DECLARATION

I hereby declare that this dissertation is my original work; every cited or text have been properly referenced and has not been previously submitted in part or totality for another degree in this or any other University.

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………………………………………. ……06/02/2021………

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DEDICATION

I would like to dedicate this thesis to my parents, Baboo and Ishara Sewnarain, to my wife, Sandika Sewnarain, my brother, Shalendra, and my sister, Reshmika, without whom, none of this would be possible.

Through their ongoing strength and support during my studies, I have had the courage to fulfil my dream and complete my degree of Master of Engineering. I would like to thank every one of them for their support, for their patience, and for their belief in me throughout this journey.

Shikhar Sewnarain

ACKNOWLEDGMENTS

It was difficult to envision the final stage of this journey, which I embarked on so many years ago, but I can honestly say it would not have been possible without the strong support base that has been with me every step of the way.

There were many challenges, some of which seemed insurmountable at the time, but I have learned something new from every challenge, and wouldn't be the person I am today without these experiences.

I would like to thank the following people for their motivation and support:

1. My parents, Baboo and Ishara Sewnarain
2. My wife, Sandika Sewnarain
3. My siblings, Shalendra and Reshmika Sewnarain
4. My supervisor and co-supervisor, Dr C. Onunka and Mr K.T Akindeji

ABSTRACT

The growth of the world population has come with an increased demand for energy since every process requires it. The most widely used source of energy for generating electricity is coal, which contributes about forty percent. However, there is a global concern about climate change, of which the use of coal- and petroleum-based fuels are stated as contributing factors. Resultantly, demand for cleaner, sustainable energy sources is on the rise. Research indicates that tidal energy is able to generate quite a significant amount of electricity. It is against this backdrop that the research presented in this thesis was undertaken, investigating the design and development of a tidal wave barrage system for South Africa. Hence, the objective of this work is to calculate, design and simulate a tidal barrage system considering the generation capacity and cost of the system.

The design enabled the calculation of the potential generation of power, as well as the required size of the tidal barrage. The calculated results were used as input for the tidal wave barrage system model, which was used in the system simulation. The system functional diagram was used in developing a function Matlab®/Simulink® model, based on mathematical models of the constituent tidal barrage components. The input parameters for this model were derived from the tidal wave data and the mechanical design properties of the turbine and generator. The Simulink® simulations showed that the tidal barrage system could generate approximately 2MW per unit - the ideal generating capacity for which each generation unit was designed. However, the Simulink® simulations do not consider the hydrodynamics of the system. The hydrodynamics of the system were simulated using DTOcean® simulation software. The input for the simulation model was derived from the theoretical calculations, the tidal wave data, the site properties, and the Simulink® results. The simulations showed a lower power output compared with the Simulink® results. The system design was completed with the results indicating there is potential for generating power from tidal waves in South Africa. The economic value and costing of the tidal plant indicate that the levelised cost of energy is comparable to that of existing tidal power plants.

This thesis will assist in paving the way for further studies into the utilisation of the country's tidal energy, with a recommendation that data for specific sites is gathered for assessment of the power generation capacity.

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LIST OF ACRONYMS AND SYMBOLS

A	Surface Area
A_i	Sinusoidal function of tidal current magnitude
C	Overall tide coefficient
CAD	Computer Aided Drawing
CO_2	Carbon dioxide
C_{spring}	Spring tide medium coefficient
C_{neap}	Neap tide medium coefficient
D	Diurnal
D_t	Turbine runner diameter
DAW	Department of Water Affairs
DTP	Dynamic Tidal Power
d	distance
E	Energy
EMF	Electromotive Force
E_p	Potential Energy
GHG	Greenhouse gases
GJ	Gigajoule
GW	Gigawatt
GWh_r	Gigawatt hour
g	Acceleration due to gravity
H	Wave height
H_o	Tidal range

H_s	Significant wave height
I_d	Direct stator current
I_q	Quadrature stator current
J	Combined coefficient of inertia for the turbine
Km	Kilometre
Km^2	Kilometre squared
kWh	kiloWatt hour
k	Universal constant of gravitation
L_d	Direct stator inductance
L_q	Quadrature stator inductance
M	Mass
MW	Megawatt
MWhr	Megawatt Hour
m	mass of a molecule on earth
mph	miles per hour
m/s	metres per second
m^2	Metre squared
m^{-2}	metre per second squared
m^3/s	metre per second cubed
OWC	Oscillating Water Columns
P	Power
p	Number of Poles
PMSG	Permanent Magnet Synchronous Generator

PTO	Power Take Off
R	Rotor diameter
rad/s	Radian squared
S	Apparent Power
SAN	South African Naval Hydrography
SD	Semi–diurnal
T	Wave Period
TW	Terawatt
T_c	Wave Period
V	Fluid Velocity
V_d	Direct Stator Velocity
V_{st}	Spring Tide Velocity
V_t	Neap Tide Velocity
V_{tide}	Tide Velocity
V_q	Quadrature Stator Voltage
WEC	Wave Energy Connector
W_{yr}	Estimated energy production
W_e	Electrical Rotor
W_r	Rotor Speed
W_q	Stator Angular Velocity
B	Pitch angle
λ	Wavelength
β_{eq}	Generator damping ratio

CHAPTER ONE

INTRODUCTION

1.1 Background

There has been massive growth in the global population the past two decades, increasing the demand for energy in order to supply the growing population. The power generation in many countries is through the use of non-renewable fossil fuels such as coal for thermal power stations, and petrol or diesel for portable power generators. Solar and wind energy are also having a share in the power matrix as these energies are clean source, however highly unpredictable. For a country like South Africa, tidal wave power can add to the power generation, and, as a clean source, can decrease greenhouse gas emissions. Tidal energy can be predicted with high accuracy, and therefore planned with higher certainty [1].

Tidal power is produced by the gravitational interaction between the sun and the moon which affects the sea. Therefore, tidal energy is effectively a form of hydropower which captures the energy in tides and converts it into electrical energy [2].

The development of tidal wave power plants started in the 1960s with developments in Saphale, India, Cumberland Basin, Bristol Channel (Flat Holm) and La Rance (France), Russia, Canada, China and South Korea [1, 4]. These developments showed great potential in harvesting tidal wave energy so as to generate clean, renewable electricity.

The La Rance installation is a 240MW plant, and the Bristol Channel plant is a proposed 7980MW installation. The Bristol Channel installation, if implemented and completed, is greater than the total installed capacity of many African countries. South Korea developed a 254MW plant in the Sihwa Dam, and Canada has a 20MW system [3]. A tidal barrage can have an installed capacity of up to 8GW with an annual generation capacity of up to 23000GWHr, assuming unlimited resources and space. Thus, the tidal barrage can supply more than three million people [1].

However, the developments are highly capital-intensive because a lot of money is invested in research and feasibility studies [5, 7]. These studies help in determining the surface area required, the typical location for the installation, the rated turbine parameters, and the number of generating units required. The tidal wave barrage has an additional cost of building the damming wall before installing the generating units. Therefore, there is a need for thorough research into the power plant.

The feasibility studies are also guided by the available technology for use in the generation plant. The three marine-power generating schemes that have been studied include the tidal stream generation, the dynamic tidal power generation, and the tidal barrage generation systems [1, 3, 6, 7]. Of these schemes, only the tidal barrage scheme has been implemented at full scale and evaluated for different places, [3] while the other schemes are still in the research and experimental modelling phases.

Apart from the generating schemes, research is being conducted into the use of tidal lagoons and fences. With regards to generators, there is research into the turbine designs so as to maximise generation, considering that the tidal energy generation is not continuous [8, 10]. This research is important because there is a need to offset the initial costs of developing the tidal wave power plant.

The decision to start a research and development programme for tidal generation is first determined by the available tidal resources for a site. A typical site should have high amplitude tides, because the power generation depends on the tidal range which determines the available water head. This is evaluated as the difference in magnitude between the high (spring) tide and the low (neap) tide, ultimately determining the available potential energy. Therefore, it’s vital that as much tidal wave data is gathered from different sites as possible. After finding the location with the best tidal wave amplitude, velocity and the largest tidal range, further research is conducted on the geographical and ecological characteristics of the place. For South Africa, such research has been done [11, 12].

The geographical characteristics determine the difficulty or ease of developing a plant at a site. These will also determine the investment required in exporting the generated energy from the site. A good site should have well-established roads for transportation of equipment and components, and the sea bed should have a relatively gentle gradient for easy installation of components. After a site has been identified according to its geographical characteristics, research is undertaken to determine the ecological impact of such a development [7, 13]. The socio-economic impact assessment will give a clear indication of the costs and benefits of developing a power plant at a particular site.

The Kyoto Protocol, which includes signatories from a number of countries, seeks to lower carbon emissions by a certain percentage over the years [14]. Some of these countries are landlocked and have limited options for power generation without using fossil fuels. However, South Africa has many coastal areas which it can utilise. The implementation is limited by the initial capital requirements for the construction of the plant, however, the afore-mentioned examples show it is worth investing in.

1.2 Motivation

Tidal technology has received considerable attention, and the aforementioned developments have shown that the technology is a viable option for generating power. South Africa has good potential for utilising tidal technologies and, it is this fact which motivated the investigation into the design of a tidal barrage power plant for South Africa. This will enable the system to increase the country’s generating capacity while also lowering carbon emissions produced - if the generation is to be increased by building thermal power stations using coal.

1.3 Aim and Objectives

1.3.1 Aim

The aim of this study is to design, model and develop a tidal wave barrage power plant for South Africa.

1.3.2 Objectives

The specific objectives of this study are to:

1. design the tidal wave barrage system
2. calculate and simulate the tidal wave barrage system
3. determine the generation capacity of the designed tidal barrage system
4. determine the cost of energy of the tidal barrage system

1.4 Contributions of the thesis and outline

The thesis provides substantial contributions to the development of renewable power generation systems in South Africa through the following:

i. The theoretical design of the system adds to current knowledge on tidal wave power generation systems in general, and for South Africa in particular.
ii. The modelling of system components can be used for further studies by changing the design parameters.
iii. The simulation results are useful in designing new systems at different locations since they give a clear depiction of the system results.
iv. Part of the results from this work was presented at the 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), Durban, South Africa, 6-7 August 2020. The paper is published on IEEE Xplore with details below:
   - S. Sewnarain, C. Onunka and K. Akindeji, "Assessment of Tidal Energy as Alternative Energy Source in South Africa," 2020 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD), Durban, South Africa, 2020, pp. 1-7, doi: 10.1109/icABCD49160.2020.9183862.

1.5 Thesis Organization

The thesis is developed from the above introduction. Chapter Two is a presentation of the literature related to tidal wave theory, as well as the tidal wave power generation. The chapter outlines the theory behind the system components and how they are modelled mathematically.

This information forms the basis for Chapter Three which is a presentation of the design of the tidal power plant system components. The designs are presented based on existing theories, making it easy to link the different components into a complete unit. The models developed in Chapter Three, together with the calculated values, are then used in Chapter Four for system simulation.

Chapter Four gives detailed models of the tidal power plant components and the system as a whole. The mathematical models are mainly applied in the Matlab®/Simulink®

simulations of the system components. The simulations use the results of the theoretical design calculations presented in Chapter Three.

DTOcean® software simulations presented in Chapter Four show the hydrodynamics of the system - important in determining the power generation capacity of the system. Chapter Five shows the economics and costing of the tidal plant. The results are shown in the concluding chapter, Chapter Six.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter introduces the study's conceptual base by providing background on tidal energy and outlining the challenges in harnessing this technology for enhanced sustainability. This is followed by a review of the transformation process, from a tidal wave into electric power, as well as the generation techniques, including turbine of tidal currents, barrage, integrated tidal energy, and lagoon. This culminates in the various benefits of tidal power, once harnessed. The basis of this system design is presented through the mathematical modelling of the constituent components of the power plant. The challenges and disadvantages of this novel energy source are highlighted to ensure necessary precautionary measures are implemented; before the conclusion of the chapter.

2.2 Background of tidal energy

Tidal energy, considered the future of electrical energy, is an alternate means of generating electricity which utilizes the power of ocean waves. This form of hydropower is able to convert the tidal power from tidal waves into electrical energy. One constraint is the high set-up cost since the power transformation includes dynamic tidal power, axial turbines, tidal lagoons, turbine design, and crossflow turbines. However, due to the tidal wave predictability, this renewable energy source is capable of generating electricity with the initial costs offset over time. Another constraint related to tidal energy is a lack of available sites capable of converting the tidal power into electricity. The justification is that flow rate speeds and tide range are necessary for harnessing and converting tidal energy.

Europe and the North American Atlantic Coast are home to tide mills. The mills store tidewater in the reservoirs, and, when the water runs back, it transforms this movement into mechanical power through the water-wheels and later electrical power. The oldest incidence of conversion of tides to electricity was a grain mill. It has further been enhanced during the 19th century when a waterfall from height was utilized in spinning turbines in generating electricity.

The two significant tidal plants in existence are France's Rance Station and South Korea's Sihwa Lake Station. Ten turbines produce an output of 254MW at each of the power stations [15].

It’s important to note that tidal waves rely on the moon and sun’s position of the sun and the moon, as well as their respective variations all year round. Although the standard approach of generating electricity from hydroelectric and tidal waves is similar, however, the two differ in the direction of the flow of water. The former provides for water flow in one direction while the latter provides for bidirectional flow [16].

Earth’s gravitational pull results in tidal motion, and the kinetic energy is generated from the water flow. This energy, known as tidal currents, is the regular movement and flow of water that drives the turbines to produce electricity. In summary, the ocean current, wind, and tidal waves are carefully harnessed and transformed into useful electrical, which is usually large scale and sustainable.

Turbine blades are designed to produce electric power, whether the moving water flows out or in. The rotor blades are designed to move in both directions, thereby elevating the design costs, as the reversible pump generator is relatively costlier with respect to single-direction one.

In reality, the prospect of a globally sustainable energy future is to optimally harness ocean energy reserve. Through this energy, we are able to create sufficient electrical power, reduce fossil fuels use, thereby reducing worldwide carbon emissions and decreasing harmful effects associated with the ocean.

Current forecasts indicate that by the year 2050, about 337 Giga Watts tidal power will be generated globally. The tidal use across the world has been measured at 2.5 Tera Watts, and the UK is regarded as the number one and global leading nation in ocean energy resource innovations. It is projected that sea along the UK coastline would produce up to 10% of energy from the tides [17].

Global efforts to advance renewable energy technologies have resulted in many countries proposing policies reliant on increased, extensive, seaward wind power for generating electricity [17].

2.3 Physics of tides

Tidal energy, which is a result of the gravitational pull, existing in between the earth and the sun or moon on a particular molecule. The pull is estimated as a force as given by [18]:

$$F=\frac{KxMxm}{d^2} \tag{2-1}$$

Where, M is the mass of the sun or moon, m is the mass of the molecule on earth, K is the universal constant of gravitation and d is the distance between the bodies

The force which the sun gives off is around 2, 17 times below the effect that the moon gives off. The gap in between molecules and the moon varies as the earth in the solar system is spinning. In daylight, the earth is comparable to both the moon and the sun, and indeed the gap seen between a molecule and the pulling surface is shorter than it was when the molecule is at the horizon. Likewise, whenever the molecule seems to be on the Earth's night light time span, the length is longer, and indeed the molecule moves away from the Earth surface. Tidal waves and the ocean currents are as a result of the earth rotation and gravitational pulls, oceanic factors, and the sea level [18]. This is further expatiated in Figure 2-1.

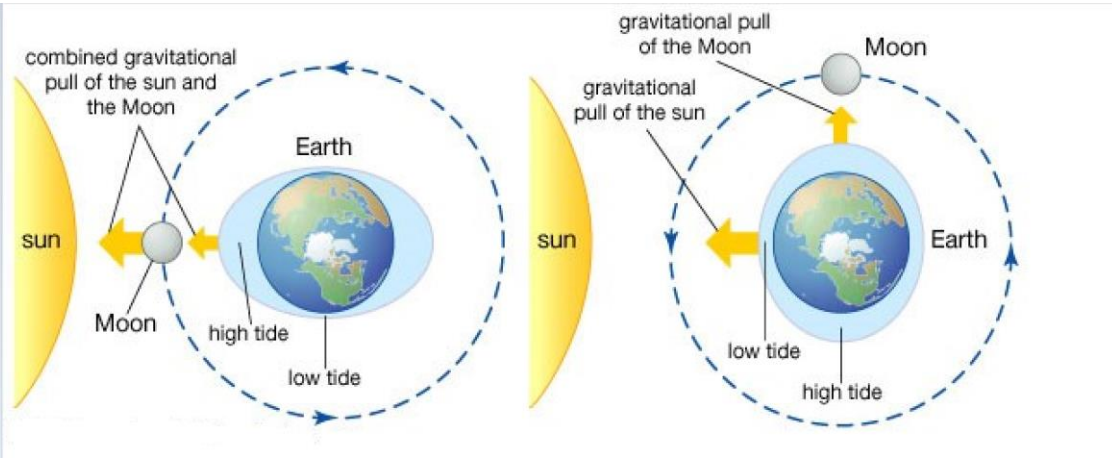


Figure 2-1 The formation of tides [19]

2.4 Ocean and Tidal Currents

Changes in the tides move ocean water volumes, thereby creating tidal current energy. From this tidal shift, kinetic energy is able to be captured. The tidal cycle causes daytime and semi-daytime currents, resulting in tidal current energy. Tides trigger kinetic motions that are stimulated near coasts.

The latitudinal movement of winds moving clockwise in the northern hemisphere and in the southern hemisphere anti-clockwise is creating out-surface currents in the sea. These are the streams that typically work in deeper waters, which have weaker fluxes than mare currents.

There is present activity both in the deep sea and in close-shore tidal flows. These deep sea currents, which have low variability, will flow in the same direction, some of which offer sufficient current rates to initiate existing expertise. Those comprise the current from Mozambique off South Africa, the current from Kuroshio off Southeast Japan, the current of East Australia and the Gulf Stream off North America. [17, 20, 21].

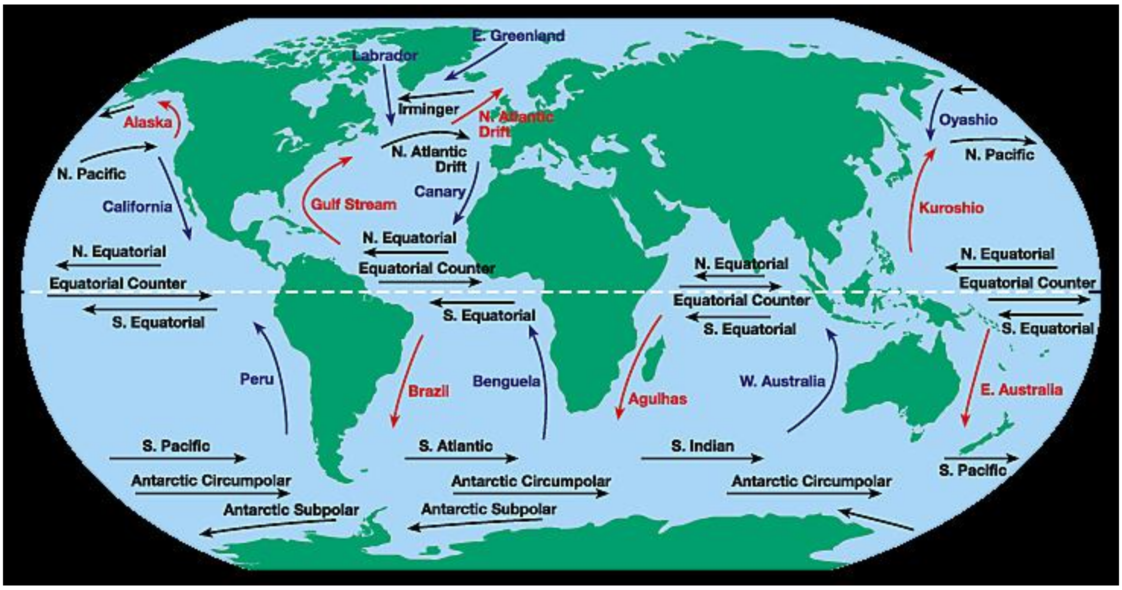


Figure 2-2 Water ocean current [20].

There are several devices being developed to extract kinetic energy from tidal, river and ocean currents, although tidal energy converters are currently the most commonly implemented. Tidal and ocean current turbines differ in that ocean current flows are unidirectional, while the tidal current system will generally require infrastructure that differs in design. [21, 22].

2.5 Energy from the Wave

As wind travels through the surface of the ground, ocean waves are generated with the air/ground connection that transfers a proportion of wind power to the water and, therefore, also generating waves. There are two types of wave energy; potential and movable kinetic energy.

Potential energy is contained in the water mass, and in the water particle movement, kinetic energy is created. Wave scale and duration depend on wind direction, period, and sea length across which it falls wave frequency and distance, which determines the amount of energy transferred.

Sea waves are energy-efficient since they can fly vast distances. Waves are measured using a variety of strategies, among them; numerical modelling of wind waves, wave buoys measure, and measurements via satellite. For water depths of 20m or lower, wave-measuring buoys are the preferred device, and measurement via satellite has risen in popularity since 1991, with altitude meter providing crucial measurements related to power and height of the wave. The measurement precision of the numerical modelling of wind waves is detailed, precise and error-free - particularly for typical wave states – spectra direction computation along the sea while using the field of wind as input [23, 24, 25].

Figure 2-3 indicates the annual wave mean-power distribution scale worldwide offshore. The highest power rates exist on the continent's west coast, where the most powerful winds are produced. [20, 21, 22].

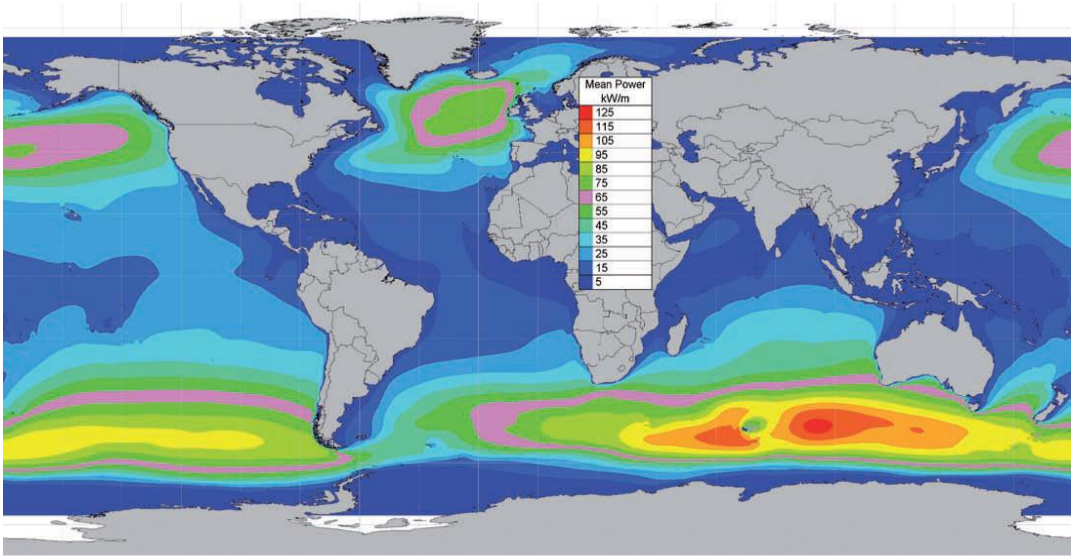


Figure 2-3 Maps of the world average offshore wave capacity [25].

Energy wave technologies that reflect a range of concepts have been technologically advanced as a way to demonstrate the conversion of wave energy into useable energy forms. These technologies consider a variety of variables, among them the form of wave contact, depth and distance from shore with respective movements. Resonance provides the required movement to operate flotation devices– through the holding and releasing of moving parts to accumulate sufficient potential energy.

There are over fifty wave energy systems at different levels of production according to recent assessments. Large-scale wave energy production would need clusters of systems instead of larger systems, including turbine generators being the chosen alternative for different site conditions. Similar methods for classifying wave energy structures have been designed [26].

There are currently a number of wave and marine current energy conversion concepts, all differing in both energy extraction and design. Three categories can be classified in the energy converter of waves as:

1. Oscillating water columns (OWCs) take energy from within a chamber or hollow oscillation of ocean water induced by wave motion
2. Overtopping devices systems cover reservoirs of waves that are accumulated over sea floors.

3. Wave activated body concept, as similarly referred to as wave-power absorption by oscillating bodies.

A structure is able to capture the energy and convert it into mechanical energy. The mechanical energy is converted into electricity using rotating generators and later integrated into the grid system [27]. Figure 2-4 displays a hydrofoil concept of system design.

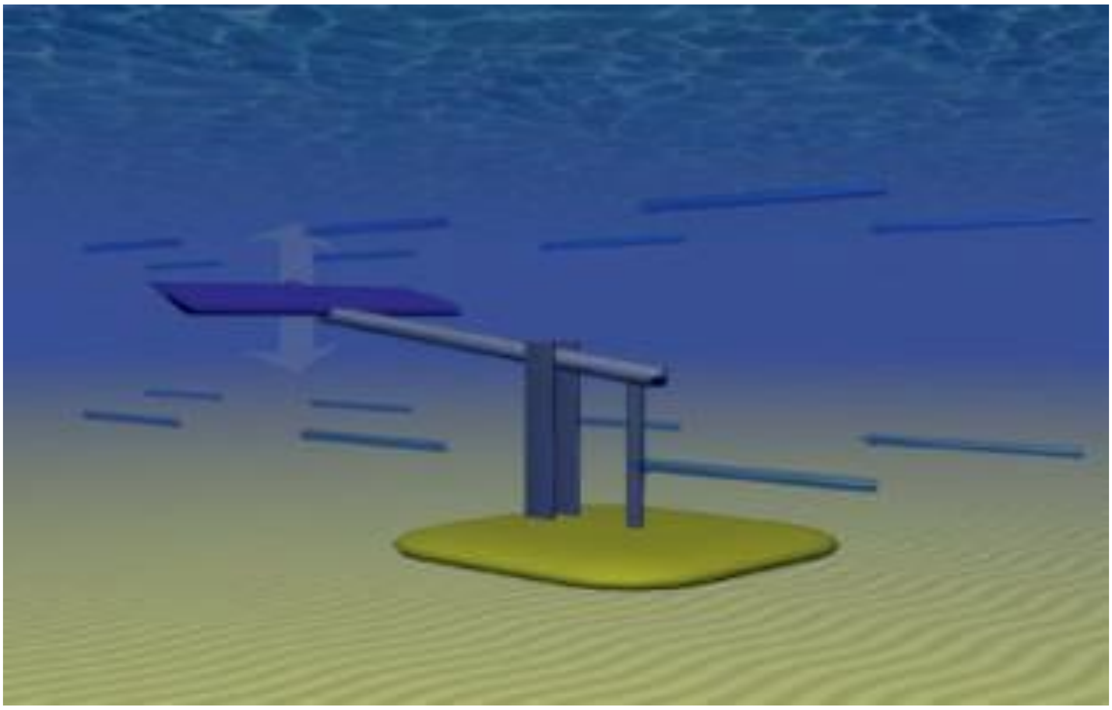


Figure 2-4 Hydrofoil concept of system design [28].

2.6 Conversion process of tidal wave power to electricity

Sea tides and sea waves allow for the harnessing of tidal power, with the gravitational pull of the earth resulting in energy peaks, as stated earlier. Kinetic energy from the ocean creates currents, and such a powerful pull produces a surge of the seawater, building a wave of massive kinetic energy. This energy raises the sea or ocean level, and this elevated water meets the shallow areas on the shoreline to create a wave. The moon's axis and the earth rotation contribute to the steady acceleration of the wave. Basically, the force of the tidal wave is generated as it is the product of orbital characteristics of the earth – the mechanism of lunar rotation. A tidal generator converts this mechanical energy into electrical by rotating the turbine blades bi-directionally, creating an inexhaustible energy source. The rotational force triggers a loss of mechanical energy by the tides. [29].

2.6.1 Wave energy conversion

Wave-created ocean energy can be derived from different technological principles. Wave power transformation - related to the wave height and period – is a result of wave motion.

Under predictable conditions over a number of days, Sea waves may have broad energy flows. The energy E is given by the power of the wave front by the unit wavelength in the direction of the wave [30]:

$$E = \frac{1}{16} . \frac{\rho g^2}{\pi} . (H^2\ T^2) \qquad (2\text{-}2)$$

It is the cumulative excess energy in water (kinetic and potential) in continuous-wave movement. Where g is the gravitational acceleration or standard gravity (m/s^{-1}), ρ is the seawater density (kg/m^3), T is the period of the wave (s^{-1}), and H is the crest height of the ocean wave (m) [30].

The power (P) of a wave front is given per unit width [30]:

$$P = E = \frac{1}{64} . \frac{\rho g^2}{\pi} . (Hs^2\ Te^2) \qquad (2\text{-}3)$$

Where Te is the period, Hs is the significant height (m), and P is power (W/m) of the wave.

The transition to electricity relies on an evolving energy source and period, which the transmission system has to tackle both until the transfer takes place. Curtailing the power generated to the 50Hz grid frequency is indeed a critical task. The process is performed through the power-take-off operation (PTO), such as the generator mechanism, turbine engine, and other power-starting devices that can be converted in order to generate usable electricity [30].

2.6.2 Tidal range

Tides are the increase in the height of the ocean as a consequence of the tidal and rotational forces that occur between planet earth, moon, and sun. A large proportion of continental coasts are semi-diurnal, experiencing two high tides and two low tides daily. Other coastal areas are diurnal, experiencing one tide per day.

Tidal amplitudes will also vary according to the relative locations on the earth's surface with respect to the sun and moon. When the position of the moon and the sun align with that of the earth, the spring tides occur. However, the neap tides take place while the earth-moon axis's gravitational powers reach 90 ° to the earth-sun axis. The range of the tide may be predicted-with a significant degree of precision-decades in advance, with unchanging control and no climate change resource uncertainty [30].

Estuarine developments have formed the basis for the advancement of tidal range power. A dam contains an estuary and then generates a large reservoir and requires traditional low-head hydro turbines. The new emphasis on offshore reservoirs – often referred to as tidal lagoons - which are located away from estuaries. Its research incorporates devices suitable for industrial use, with the bulb-turbine the common conversion mechanism to generate electrical energy from the tidal range. This can be demonstrated in the northern French La Rance power plant with a 240MW capacity production. Sloping coastlines and tidal plants, like a Severn Estuary between southwest England and southern Wales are suitable locations for bulb-turbines. [26].

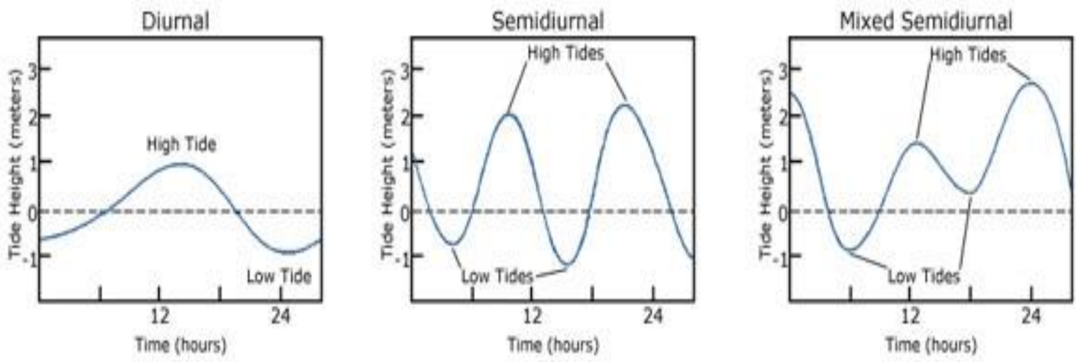


Figure 2-5 Various tide types [33].

2.6.3 Tidal power

Tidal power is power produced by oceanic tides generated by the rising or declining rates of water, as a result of the rotational movement of the sun, moon, and earth [34].

These tidal movements of oceanic water can generate electrical energy through the combination of a small dam at the entrance of a bay with tides at high levels. This dam catches the wave and creates a disparity in the water level that generates potential energy. When the dam gates are opened, and the water enters the lower floor, the potential energy generates kinetic energy. The kinetic power is then converted into kinetic rotational power; the turbine movement produces the electrical energy [34].

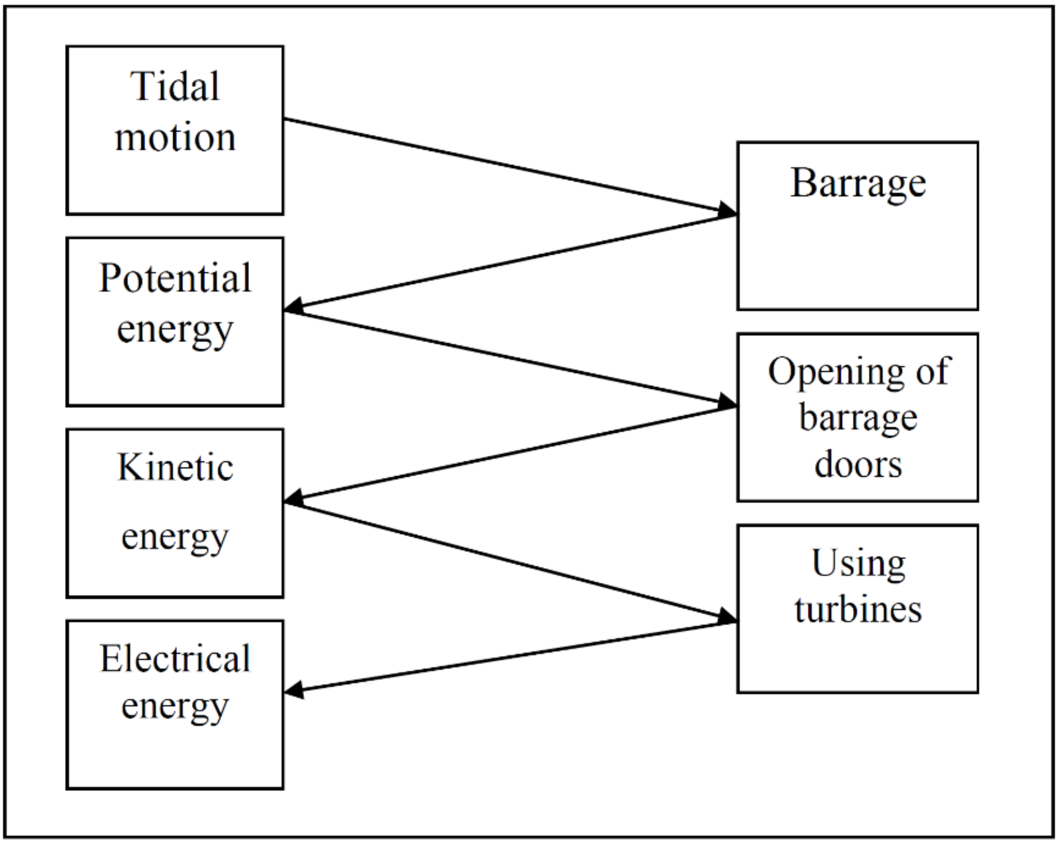


Figure 2-6 Block demonstrating the tidal energy transitions to electricity [34].

2.7 The operating system of tidal power generation

At the entry of a gulf, a dam is built with water volumes on all sides of the channel. The channels within the dam created to allow for water flow. This flow forces the turbine to rotate, thereby creating electricity. The basic scheme for a tidal plant is shown in Figure 2-6 [34].

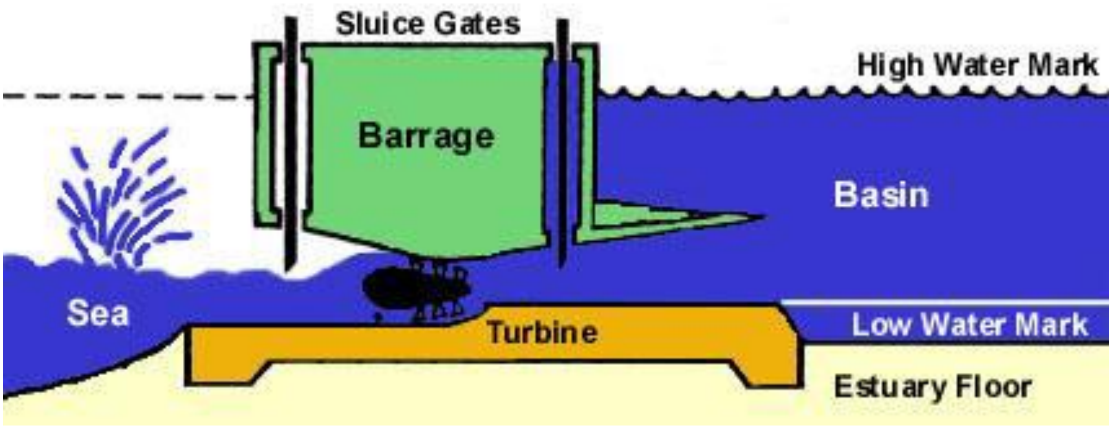


Figure 2-7 Overall tidal power plant scheme with various elements [34].

2.7.1 Tidal power plant modules

- **Barrage**

The tidal barrage employs a damming mechanism to separate the seaside from the land side of the barrage, with water s then impounded in the basin during high tide. The choice of the site should be such that the sea level rises significantly in order to give good water head for power generation [34, 35].

- **Turbines**

There are different turbine types, among them the horizontal-axis, axial, and vertical-axis cross-flow turbines, as well as the open-centre turbines. The open-centre design has blades mounted inside the shaft, which is housed in a static tube. This design mitigates the need for a gearbox for coupling [34, 35].

Figure 2-8 shows the two common types of turbines used in marine power generation schemes. The horizontal-axis axial turbine is commonly used due to its efficiency and stability.

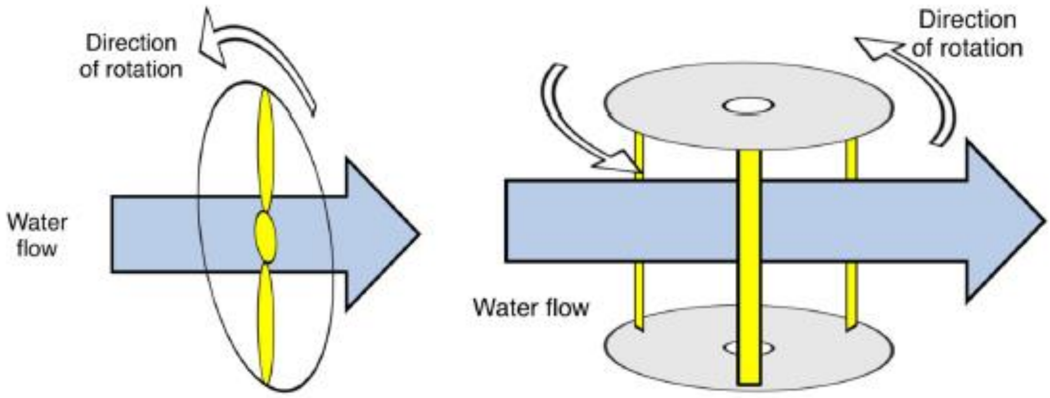


Figure 2-8 Axial flow and cross-flow turbine presentation relative to direction of water flow [35].

Figure 2-9 shows an open-centred turbine with details of the coupling mechanism. This design eliminates the need for an independent gearbox system, and this, in turn, improves the efficiency of the generating system.

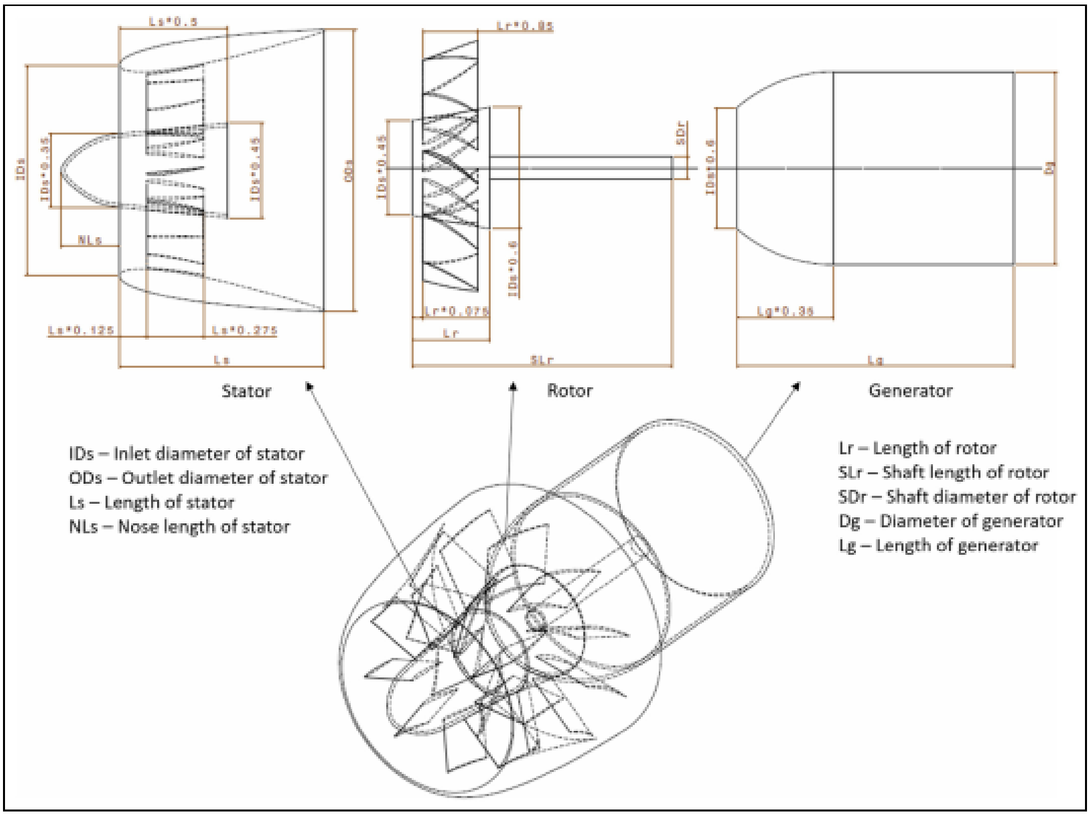


Figure 2-9 The open-centred turbine and system units coupling diagram [36].

There are several types of turbines based on the basic two types above. These include bulb turbines, tabular turbines, and rim turbines [34].

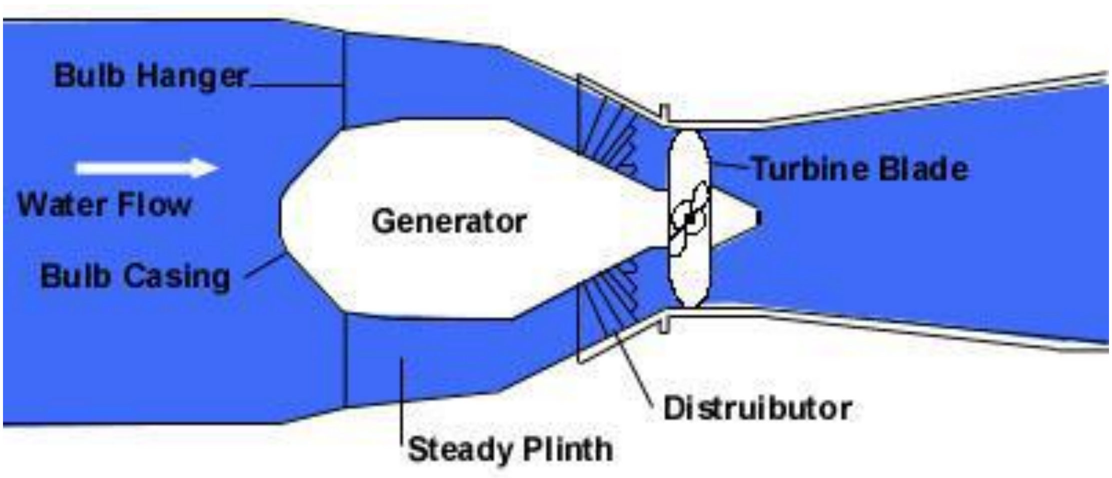


Figure 2-10 Bulb-type turbine [34].

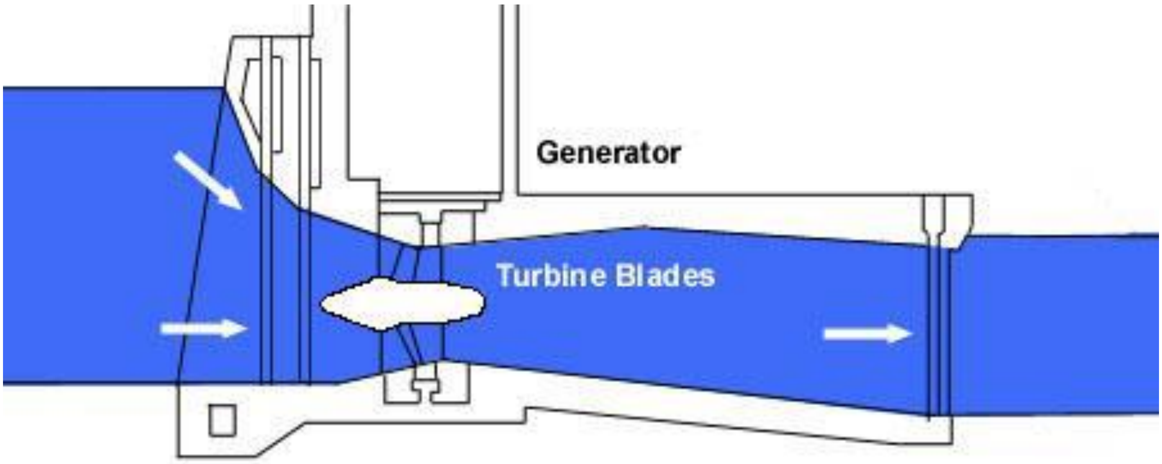


Figure 2-11 Rim turbine [34].

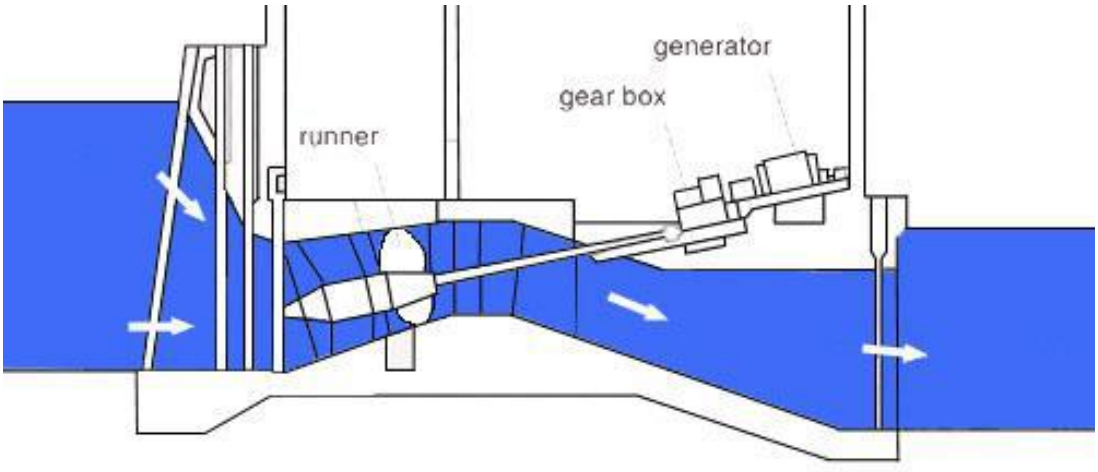


Figure 2-12 Tabular turbine [34].

- **Sluices**

The sluice gates allow water to move through the dam [34, 35].

- **Embankments**

Embankments impede water flow at individual dam sections, allowing stress-free maintenance of the connection of electrical wiring [34, 35].

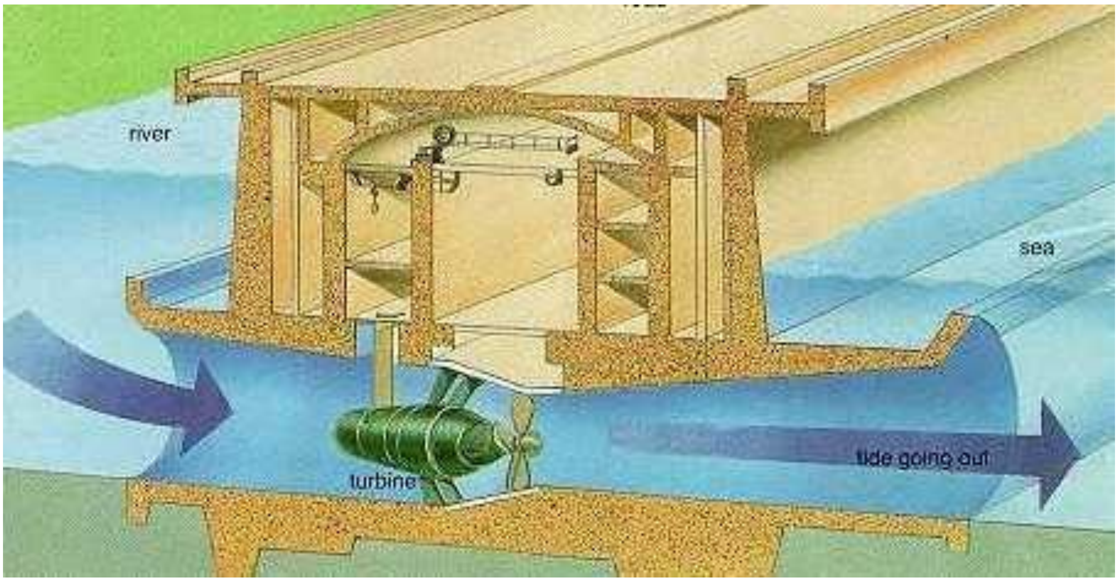


Figure 2-13 The embankment [34].

2.7.2 Power production approaches from tidal energy plants

2.7.2.1 Ebb method

Ebb generation is when the water is impounded in the reservoir and power is generated when the reservoir level is high enough to create head for generation. In this scheme, the water flows into the sea from the reservoir to generate power as shown in Figure 2-13 [34].

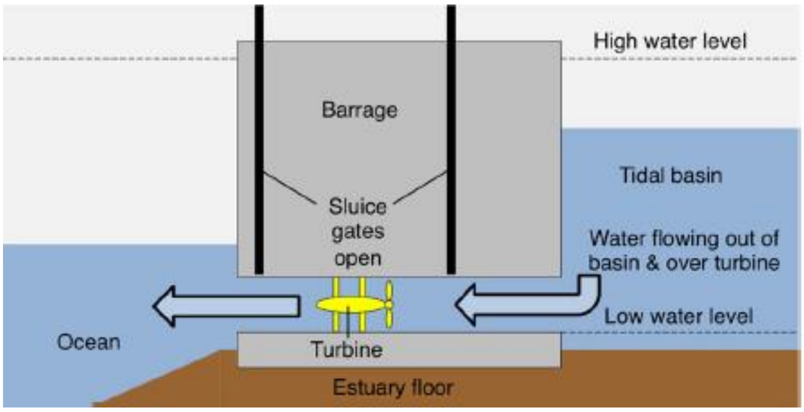


Figure 2-14 Ebb generation scheme [37].

2.7.2.2 Flood method

Flood generation is when the tide is high enough to create a head that can generate power as water enters the reservoir from the sea side - as illustrated in Figure 2-14 [34].

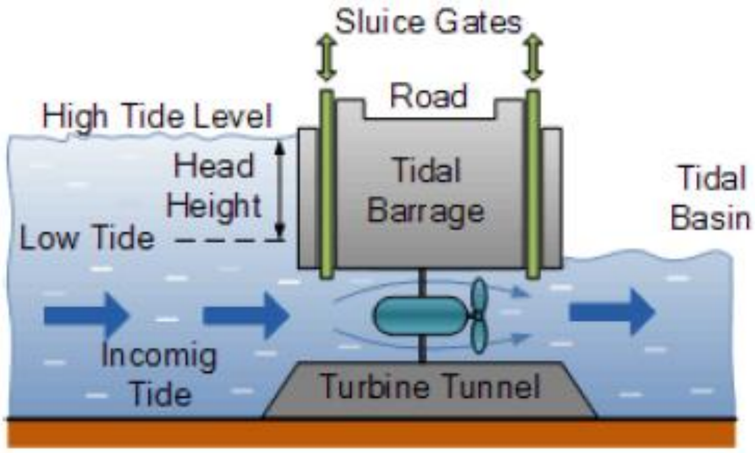


Figure 2-15 Flood generation scheme [37].

2.7.2.3 Ebb with pumping technique

The turbine pushes water into the reservoir by raising the level of water by creating a wide gap. In the ebb point, the water leaves the basin and creates energy for a significant duration. [37].

2.7.2.4 The two-way power generation technique

The reservoir is loaded; the entry is opened so that water flows may provide energy. If the loop continues, the turbine rotation is flipped, and the entry locked, with the water held behind the dam. Once a good water head is formed, the entry unlocks, which causes the process of water supply to move into the reservoir. [37].

2.7.2.5 Two basin generation technique

There are two basin technique -a high-level basin and a low level basin-and the turbines in the wall which separate the two basins. The high-level sea bottom is loaded with the low-water bottom floor supplied by the turbines from the high-floor edge. Eventually, at the low tide, the low-level bay is drained [37].

2.7.3 Generating Techniques

Several of the approaches used in the conversion of the energy to electrical power are:

1. Tidal stream generator
2. Tidal barrage
3. Dynamic tidal power
4. Tidal lagoon

2.7.3.1 Tidal stream generator

The generators here are built on subsurface or existing tunnels to prevent damage to the surrounding landscape – to power turbines with kinetic energy from moving water. Constrictions of land required for the tidal stream generator can be man-made or natural to develop the high speeds of flow spinning the turbines. The turbine arrangement may be a vertical, horizontal, pipe, or exposed, and the engine can be operated at a higher pace when water becomes denser than air. The tidal energy flows are about 10 mph, and so the transfer is adequate for these tides, which provide higher energy rates than turbines for advanced power levels. [38].

2.7.3.2 Tidal barrage

The barrage utilizes the potential energy, alongside the change in the height difference of the high and low tide. Strategically-placed dams allow for the extraction of tide's potential energy. The arrival of the tide brings increased tidal power, which is channelled to a basin behind the dam, able to store significant potential energy.

The potential energy turns into mechanical energy as the water passes through the turbines to generate electric energy. Barrage is, in essence, dam established to capture tidal flow velocity inflow, harnessing the flow energy (potential and kinetic) for electricity generation [38].

2.7.3.3 Dynamic Tidal Power (DTP)

Although tests are still ongoing for DTP, the technique is capable of utilizing the tidal flow energy interface of potential and kinetic energies. This fundamental scheme uses coastal barrages of about 30-50km in length, opening directly into the ocean. Tidal phases in the dam build a discrete water level that makes the river flow through and out of the dam reservoir. [38].

2.7.3.4 Tidal lagoon

The latest design for harnessing tidal energy, a tidal lagoon, consists of a circular barrier built to control the water flow speed. The interior has multiple turbines capturing the potential energy the tides carry into the lagoon. The lagoon is similar in construction to the tidal barrage. However, the barrage is artificial and with both a pumping and a non-pumping arrangement. The arrangement allows for the storage of excess renewable energy [38].

Tidal power presents some environmental concerns, mostly centred on the effect of ocean currents on aquatic organisms. The spinning turbines may have a detrimental impact on underwater diving animals by accidentally killing or maiming them. However, most tidal power projects currently include a safety feature that switches off the turbine when the marine animal approaches, only switching on again when the animal is a safe distance away. [38].

Another challenge for marine life is the tidal turbine acoustic disturbance generation. Of particular concern is the hazard created by the echo, which may attract aquatic animals that cross and transfer using such acoustics. The generated electromagnetic field and the production of acoustics could impact aquatic life because such machines are situated in water, and the intensity is more substantial compared to wind energy. The frequency and the amplitude of the sounds depend on the type of energy device used. [38].

Additionally, the distant water quality may be diminished, but this depends on the project scale and capacity of the turbines used. The system can also raise the pollution in the ecosystem and trigger environmental impacts that affect aquatic animals and sea vegetation [38, 39].

In the case of a tidal barrage, environmental impact is of particular concern as each coastline ecology relies on tidal flats, thereby impacting the shoreline the redirection or inhibition of the natural water flow could possibly affect the flushing of the bay or the estuary, resulting in more suspended solids in the water. This creates higher turbidity of the water, which is uninhabitable for fish – a vital food source for birds and marine mammals. Fishing operations will decrease with spawning rivers not open to migratory fish, a socio-economic condition vital for coastal residents. Some of the positives of a tidal barrier are that it will improve exposure to land and cleaner seas for recreation – however the marine life may be entombed in the depths. [38, 39].

A major concern related to the construction of tidal lagoons is the rotating blade, which could maim or kill marine life. The acoustic waves generated by the turbines disturb the movement of marine life by impacting hearing and navigation. Changes in the sedimentation mechanisms can also have a detrimental effect on the lake or estuary [38, 39].

The generator, which is located in salt water, is also vulnerable to corrosion. Furthermore, underwater maintenance proves difficult because of the size and depth. In addressing this, corrosion-resistant metals will minimise damage. Mechanical liquids and lubricant materials also spill into the groundwater, harming local marine life and the environment. [38, 39].

During construction of the system, biological productivity increases - providing a structure on which marine organisms can grow. This allows the preservation of the system challenging and limits the harnessing of the ocean current [38, 39].

The high start-up and capital cost of the installation has been one of the reasons it’s not been quickly adopted, despite being a promising alternative energy source (renewable). Statistics suggest this green energy source can be competitive economically with attendant profit.

The cost is mainly correlated with the spinning blade and generators, each of which is specifically designed and manufactured for the individual project. The length of the tidal dam in meters and an average of kilowatts = 1 kWh = 1000 watts per hour of comparison to the total green energy output, must be determined [40].

Studies have shown that the inherent tidal wave energy efficiency ensures that the initial expense is recovered over a period of time. If the architecture is straightforward and transverse turbines are used, cost savings can be improved. The period needed for each turbine to be assembled could then be shortened, the metal required and overall mechanical output enhanced. Ultimately, harnessing tidal energy for conversion to electrical energy can be a feasible, efficient lucrative project [41].

2.7.4 Grid integration

The incorporation of sea resources into the electricity system faces various problems, including the expense of adding capacity ranges to the system. It is the high cost is related to the number of b components required to connect to the shore, including sub-sea electrical systems and undersea electrical wires. Certain regions have high tidal energy supplies but the remoteness of these locations means they are off-grid, thereby necessitating grid capacity expansion [17, 31, 32].

The variability of electricity production from ocean energy devices could result in challenges, including congestion of grid infrastructure, poor networks, and issues of system stability - linked even to technical growth. However, an investigation is being conducted to address this.

For certain instances, regions with substantial ocean energy capacity are located in places with a low density of population and limited grid infrastructure. According to the standard of service, the electricity supplied to the grid may be limited. This necessitates an electrical transmission and distribution network enhancement, thereby adding on to the initial price. The grid infrastructure codes for electrical networks allow for the stable functioning of an energy system, which details the reliability of frequency, power factor, voltage, and harmonics that a power plant has to follow. [17, 31, 32].

There is ongoing research attempting to illustrate the impact of tidal power on the electricity grid, using steady-state and transient analysis. As stated, the connection to the ocean energy to the electricity grid is strained by poor power grids in rural areas. There is no one European-standard grid code at present, but the ocean energy industry and other power supplies may conform to the related content or national grid codes.

Renewable energy demands growth, and grid integration must be done to add to network efficiency and stability. The quality of ocean power production must conform to the grid code specifications, and adequate control systems must be built for ocean power conversion and arrays. More work in terms of control mechanisms is currently needed, as this provides tremendous potential to minimize costs due to improved energy absorption whilst fulfilling specifications for the grid code [17, 31, 32].

When it comes to grid connection for tidal current technology, there is significant consideration required. Turbines need to be connected to each other through array cables, which are connected to a shoreward substation. This is connected to an offshore substation and then to the grid with an export cable. Grid connectivity is still essential as complications, and link costs may impede several projects [17, 31, 32].

Disadvantages related to marine-based technological operations include ensuring system safety and wave conversion capacity. The existing Wave converters must be built explicitly to meet the predicted harsh conditions. The wave energy modelling principle differs significantly because the intensity of a storm cannot be calculated, thereby, the design requirements of the system and the acceptable risk level of the system are calculated by a probabilistic approach. [30].

2.7.5 Social and environmental impacts

Although tidal wave energy does not produce carbon dioxide (CO_2) throughout its action, this is likely that when processing raw materials and part production, greenhouse gases may be emitted (GHGs). Researches are being carried out on the wave and tidal energy to ascertain the significance of the differences in greenhouse gas emissions generated.

In terms of avoiding the possible negative environmental impacts from ocean energy, one consideration is to restrict human beings' undertakings around the tidal plant. Increased availability of energy and the consequent regional economic development will affect ocean resources positively. Ocean energy plants are generating local employment and are also an increasing tourism attraction. Possible adverse impacts of a tidal power project involve noise pollution and landscape degradation in the region where the tidal power plant is built [17].

2.8 Potential of South Africa to harvest ocean energy

The Department of Water Affairs South African Naval Hydrographer Nelson Mandela Bay Municipality, Water Research Commission, and Afri-Coast Engineers did sea level measurements at different ports around South Africa. The areas included the Berg Estuary, Saldanha Bay, Cape Town, Bree River Estuary, Mossel Bay, Kaaimans Estuary, Keurboom Estuary, Port Elizabeth, Durban and Richards Bay, among others [42].

Research showed good tidal energy potential in Durban and Port Edward, based in KwaZulu-Natal. Durban has been selected due to the availability of data. The current speed of 1.5m/s is very common and promising good prospects for power generation [42].

Table 2-1 shows the measurements presented for Durban [42]. The location has four tides, spaced by approximately six hours. The early morning tide and midday tides are normally the highest, above 1.5m.

For Durban, the tide has an average of 0.8m high. Assuming that the generator operates for T hours per day, the available energy can be estimated. The volume of water in the tidal basin gives a rough estimate of the potential energy in the water and hence, the available power from the tidal device. The potential energy is given by [43]:

$$E_p = 0.5 A_b \rho g H^2 \qquad (2\text{-}4)$$

A_b is the basin surface area in m^2, ρ is the density of the salt water approximately 1026 kg/m^3 for South Africa at 15^0C [44], g is the acceleration due to gravity, 9.81 $ms^{2,}$ and H is the hydraulic range in metres.

Table 2-1 Durban sea measurements [42, 44].

Water depth (m)	100m	200m	300m	500m	1000m
Distance offshore (km)	11	12	14	17	20
Current speed (m/s)	1.3	1.5	1.5	1.5	1.4

Using ebb generation, the power generated is given by [43, 45]:

$$P = \frac{E_p}{t} \in = 0.5A_b \rho g H^3 \quad (2\text{-}5)$$

If the water time elevation series is known inside and outside the barrage, theoretical energy passing through the turbine can be determined in any time intervals. The energy can be expressed as [43]:

$$E = \int_{t1}^{t2} \left[-\rho A \frac{dh}{dt} g\big(h(t) - h(to)\big)\right] dt \quad (2\text{-}6)$$

Assuming the barrage surface area and discharge remain constant during the time interval, then the discharge Q is given by [43]:

$$Q = -\frac{Adh}{dt} = \text{constant.} \quad (2\text{-}7)$$

The equation 2-3 becomes [43]:

$$E = \rho g Q \int_{t1}^{t2} \big[\big(h(t) - h(to)\big)\big] dt \quad (2\text{-}8)$$

Discharge [43]: $$Q = AH_0/t \quad (2\text{-}9)$$

Where Q is in m^3/s, A is the basin surface area in $m^{2,}$ and H_0 is the tidal range in metres. The density of South African seawater is approximately 1026 kg/m^3 at 15^0C [44].

2.9 Tidal barrage power plant modelling and design theory

Tidal barrage systems use the tidal range for power generation. The design is based on the available surface area for the reservoir, the availability of good tidal currents, and the implementation technology. The components making up the power plant can be modelled using mathematical expressions. These expressions are used in the calculation of the design, as well as in simulations.

2.9.1 Tidal currents

Tidal currents can be represented by three-dimensional, non-linear variables, notably the tidal turbulence, over tides, and eddy fields. These are represented in Figure 2-16.

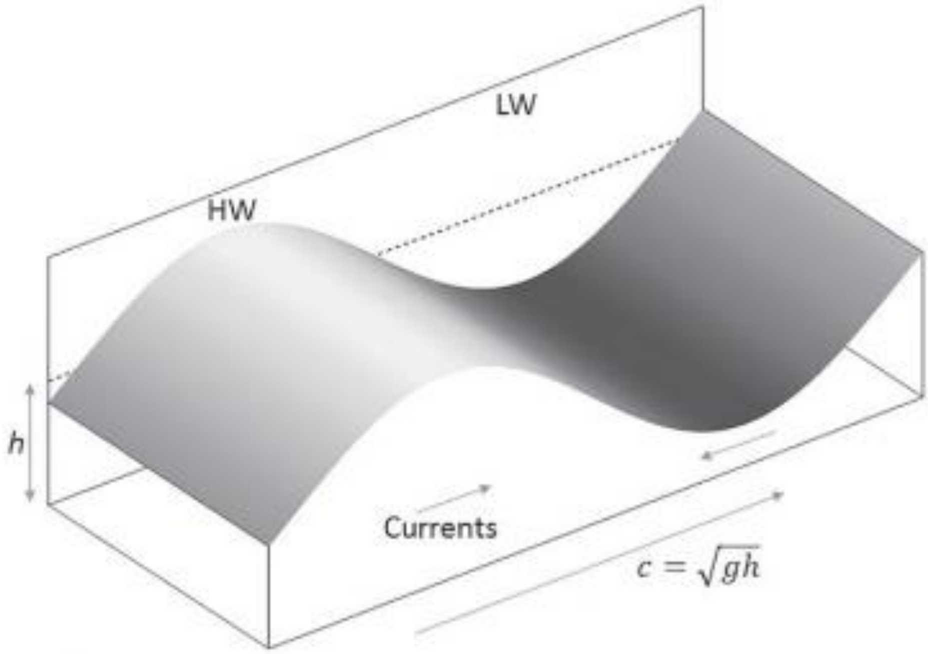


Figure 2-16 Tidal current three-dimensional representation [46].

Tidal propagation fundamentals give rise to the tidal-phasing concept. The tidal velocity in shallow water can be given as [47]:

$$c = \sqrt{(gh)} \qquad (2\text{-}10)$$

Where c is the wave celerity (m/s), g is the gravitational acceleration (m/s^2), and h is the water depth.

At 100m depth, the estimated wave celerity, $C=\sqrt{9.81x100} = 31.32$m/s.

For illustration, depth of 100m is selected as being representative of Durban coastal waters. From this, the wavelength λ of the tidal wave can be calculated as [47]:

$$\lambda = cT \tag{2-11}$$

$$\lambda = 31.32 \times 12.4 \times 3600 = 1.4\text{km}$$

Where T is taken as the time period of 12.4 hours of the main tidal component.

2.9.2 Modelling the tidal power plant from the current energies

The total kinetic power in a marine current turbine has a similar dependence as a wind turbine, and is governed by the following equation [35]:

$$P = ½ \times \rho A v^3 \tag{2-12}$$

Where ρ is the fluid density, A is the cross-sectional area of the turbine, and V is the fluid velocity. A marine energy converter, or turbine, can harness only a percentage of this power due to losses; hence the power equation includes the power-efficient and becomes [35]:

$$P = ½ \times C_p \rho A v^3 \tag{2-13}$$

The power per unit area, power density [35]:

$$P_d = {}^{1}\!/_{2}\, C_p \rho V^3 \tag{2-14}$$

Mean power density of a period T is given by [43, 48]:

$$P_{dm} = \frac{1}{T}\int_0^T {}^{1}\!/_{2}\, C_p \rho V(t)^3 dt \tag{2-15}$$

For marine turbines, C_p is estimated to be in the range of 0.35–0.5. C is a function of tip speed ratio λ and the pitch angle β [48].

Hence:

$$P = 0.5\rho C_p(\lambda, \beta) A v^3 \tag{2-16}$$

$$\lambda = \frac{R\omega_r}{v} \tag{2-17}$$

Where R is rotor diameter and ω_r is rotor speed [48]:

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) e^{-C_5/\lambda_i} + C_6\lambda \qquad (2\text{-}18)$$

Where [48]:

$$\lambda_i = \frac{1}{\lambda 0.08\beta} - \frac{0.035}{\beta^3+1} \qquad (2\text{-}19)$$

And λ_i is the next value of λ.

Using the 1.2MW SeaGen turbine parameters for the simulation [9], it shows that a 10MW installation requires 9 generating units. The technical details for the turbine are given in table below.

Table 2-2 SeaGen turbine technical parameters [49].

Parameter	Value
Rated power	1.2MW
Capacity factor	40%
Rotor diameter	16m
Design life	20 years
Reliability	>90%
Overall efficiency	89%
Design rotor power co-efficient	0.45
Cut in speed	0.7m/s
Rated speed	2.25m/s

The power curve, shown in Figure 2-17, can be used to estimate the power output from given velocity profiles.

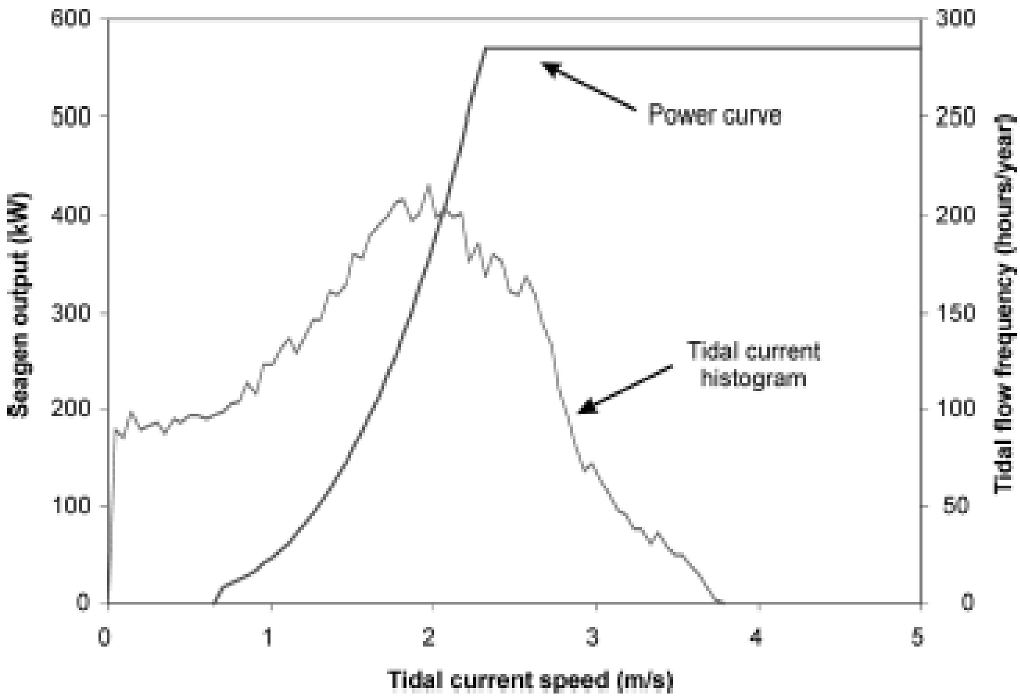


Figure 2-17 SeaGen turbine power curve [9]

2.9.3 Permanent Magnet Synchronous Generator (PMSG) model

The Park/Clark transformations are used in modelling three-phase machines since they remove the complex voltage equations and avoid the dilemma of the unknown relative rotor to stator angle.

The mathematical model of the PMSG, according to the synchronous d-q reference frame, is given by [48]:

$$V_d = -L_q I_q W_e + L_d \frac{di_d}{dt} + RI_d \tag{2-20}$$

$$V_q = -L_d I_d W_e + L_q \frac{di_q}{dt} + RI_q + \varphi_{pm} W_e \tag{2-21}$$

$$\varphi_d = L_d I_d + \varphi_{pm} \tag{2-22}$$

$$\varphi_q = L_q I_q \quad (2\text{-}23)$$

$$W_e = P\,W_g \quad (2\text{-}24)$$

Where, V_d and Vq are the direct and quadrature stator voltages, respectively, L_d, L_q are the
direct and quadrature stator inductances, respectively. I_d and I_q are the direct and quadrature
stator currents, respectively. φd and φq are the direct and quadrature stator fluxes, respectively. φq is the permanent magnet flux, W_e and W_q are the electrical (rotor) and generator (stator) angular velocity, respectively, and P is the number of poles.

The electromagnetic torque can be expressed in the same frame as follows [48]:

$$T_e = \frac{3}{2} P[(L_q - L_d) I_d I_q + \varphi_{pm} I_q \quad (2\text{-}25)$$

The above modelling equations are used in developing the simulation models of the components, and also assist in deciding the design parameters of the system components.

2.10 Advantages of tidal energy

1. Tidal energy requires no fossil fuels, making it clean and renewable
2. Tidal energy creates no harmful waste or by-products which require disposal.
3. Tidal energy creates more cost-efficient electricity for consumers
4. The visual impact of a tidal energy plant is minimal
5. Noise pollution from a tidal energy plant is minimal
6. Tides are extraordinarily reliable and predictable
7. Tidal barrages safe from land damage and floods
8. Tidal waves will not deplete [34]

2.11 Disadvantages of tidal energy

1. It is an inconsistent energy source
2. Tidal energy requires an appropriate location and relies on the moon's gravitational pull
3. Tidal streams must be robust to energy conversion

4. Distribution costs related to electricity generation are high
5. Coastal erosion could occur when tidal energy is intense
6. The tidal barrage may accumulate sand sediment, silt, and other pollutants.
7. The barrage poses a hazard by entrapping marine animals
8. Tidal power systems do not generate electricity at a steady frequency
9. Construction costs are high
10. Tidal fences could impede the movement migrating fish [34]

2.12 Conclusion

There are two methods to use tidal energy resources for power conversion in order to generate electricity. The first is to hold water in a reservoir by building a tidal barrage, and the second by utilizing natural stream and tides below the sea levels. The initial capital investments for the construction of a tidal energy conversion plant are high, as dams have to be built, turbines manufactured to specification, and support ships used bed to the project.

However, the energy produced by the fully-operational tidal plant free, clean, and renewable, making the project profitable over time. The running costs associated with a tidal energy plant are not high if the chosen location is suitable.

The key emphasis should be the flow and fall of tides, which catch the potential energy and convert it into electricity. The types of energy that will be used for the conversion process are potential energy to mechanical energy into kinetic energy into electricity.

As seen in the chapter, there are advantages and disadvantages, and some already commissioned plants are closed, there are some operational plants currently generating cheaper electrical power for consumers in industrial areas. By implementing correct technological designs and using an efficient construction process, the use of metals will decrease, and costs related to manufacturing turbines lowered.

Further to this, by selecting a central site suited to the power plant, there are fewer costs involved. That is because tidal waves and flows are a normal phenomenon that should not be introduced into the barrage or reservoir.

By utilizing metals resistant to submarine organism productivity, maintenance costs can be further lowered. This will also impede corrosive action caused by organisms, minimising the need for maintenance of the underwater generators and increasing control over turbine fluid leakage.

CHAPTER THREE

DESIGN OF THE TIDAL BARRAGE SYSTEM

3.1 Introduction

Tidal barrage systems use the tidal range for power generation. The design is based on the available surface area for the reservoir, the availability of good tidal currents, and the implementation technology. This chapter is a presentation of the design of the tidal barrage power plant. The theory presented in the Literature Review, together with other related concepts, are used in determining the parameters of the system components. The parameters of the turbine are determined from the barrage, and the design parameters are tabulated and used for the simulations that will follow in the ‘simulation chapter’.

3.2 The site selection method

The theory of the existence of tides has been presented in the Literature Review. The generated potential of the tidal barrage power plant is determined by the tide and the available surface area of the basin. The tidal barrage employs a damming mechanism to separate the sea from the coastal side of the barrage. The mechanism then allows water to be impounded in the basin when there is a high tide. The choice of the site should be such that the sea level rises significantly in order to give good water head for power generation. Tidal barrage systems use low head, which influences the choice of the turbine.

The tidal turbine application chart, represented in Figure 3-1 obtained from [50], shows the workable head and discharge that can be selected and used to dimension the barrage. The sketch in Figure 3-1 shows possible choices for the placement of the tidal barrage. The Department of Water Affairs, the South African Naval Hydrographer, Nelson Mandela Bay Municipality, the Water Research Commission, and Afri-Coast Engineers did sea level measurements at different ports around South Africa. These areas included Saldanha Bay, Bree River Estuary, Mossel Bay, Port Elizabeth, Durban, and Richards Bay, among others [42]. The design will be based on data for Durban in KwaZulu-Natal, South Africa [12, 42].

The contours in Figure 3-1 show the typical tidal range values as the waves approach the coastline. As one approaches the coast, the tidal range tends to increase. However, there is a limit to how close the barrage can be placed next to the coast because, although there is a gain in the tidal range, there is a corresponding decrease in the area covered by the basin. This area determines the amount of energy that can be created by the tidal current power-generating equipment. The angle of the barrage to the direction of the prominent tide should be close to 90 degrees, so maximum water is impounded in the basin.

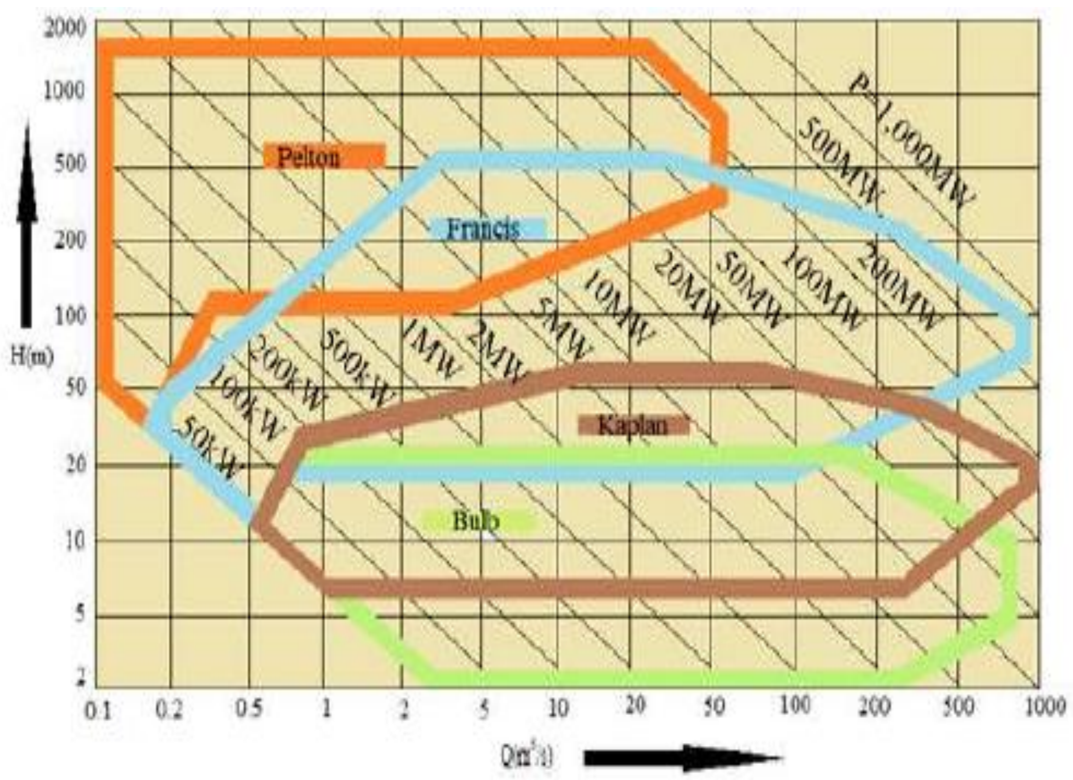


Figure 3-1 Turbine application chart.

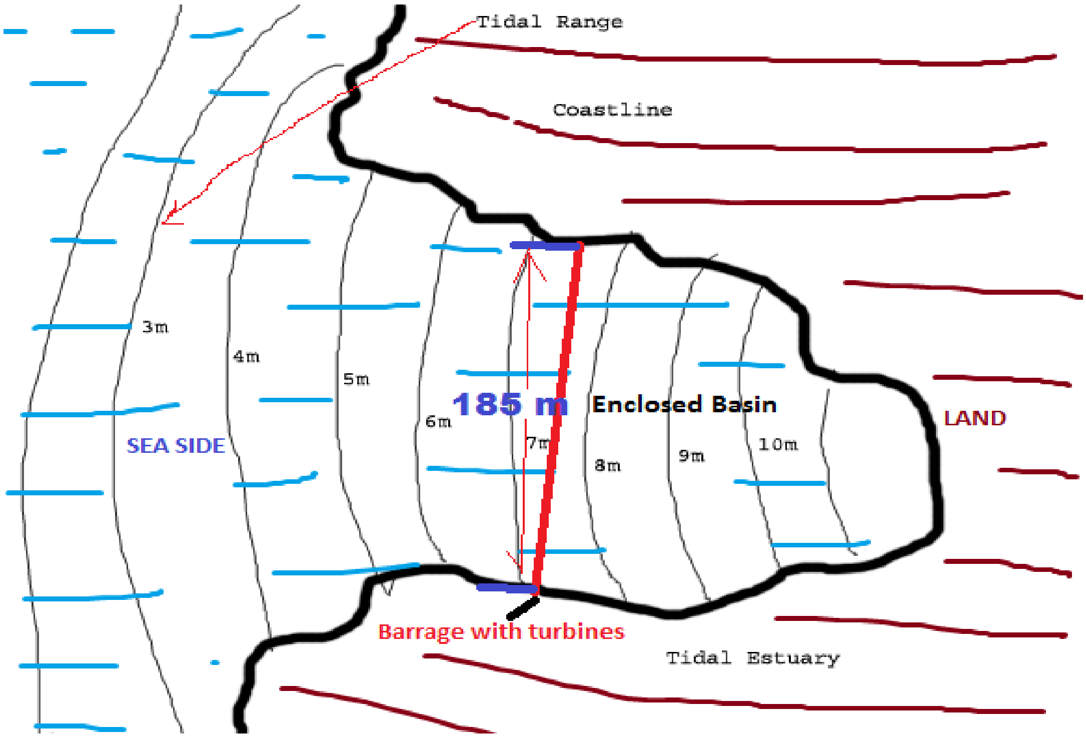


Figure 3-2 Tidal barrage physical site sketch

3.3 Tidal barrage system generation capacity determination

Research showed good tidal energy potential in Durban and Port Edward, both situated in KwaZulu-Natal, due to the prominent Agulhas current, which occurs almost daily. Durban has been selected because of the availability of data. The current speed of 1.5m/s is prevalent and gives good prospects for power generation [42].

The location has four tides spaced approximately six hours apart. The early morning tide and the midday tides are normally higher than 1.5m. The tide has an average of 0.8m-height [12, 51]. Durban has two high tides and two low tides daily. The high tides occur at approximately 12 and 24 hours, which translates to a frequency of two per day. Assuming that the generator operates for T hours per day, the available energy can be estimated. The volume of water in the tidal basin gives a rough estimate of the potential energy in the water, and hence the available power from the tidal device. The potential energy is given by [43, 50]:

$$E_p = 0.5 A_b \rho g H^2 \tag{3-1}$$

A_b is the basin surface area in m^2, ρ is the density of salt water - approximately 1026 kg/m^3 for South Africa at 15°C [44] - g is the gravitational acceleration due to gravity, $9.81m/s^2$ and H is the hydraulic range in metres.

Using ebb generation, the power generated is given by [45, 51, 52]:

$$P = \eta\rho gQH \tag{3-2}$$

The estimated energy production is given by [45, 51, 52]:

$$W_{yr} = 0.987\eta AH^2 \tag{3-3}$$

The discharge through a single turbine rated at 2MW is therefore given by:

$$Q = \frac{P_r}{\eta\rho gH} = \frac{2\times10^6}{0.9\times1026\times9.81\times1.5} = 147.2m^3/s \tag{3-2-a}$$

Assuming the barrage surface area and discharge remain constant during the time interval, then the discharge Q for five turbines required for a 10MW plant is given by [43]:

$$Q = AH_0/t \tag{3-4}$$

Where Q is in m^3/s, A is the basin surface area in m^2, and H_0 is the tidal range in metres. The generator can be assumed to operate for 4 hours; therefore, the basin area A is:

$$A = \frac{Qt}{H} = \frac{5\times147.2\times4\times60\times60}{1.5} = 7\ 065\ 600m^2 = 7.066km^2 \tag{3-4-a}$$

The potential energy in the basin at the calculated surface area is given by the equation:

$$E_p = 0.5 \times 7065600 \times 9.81 \times 1026 \times 1.5^2 = 80\ GJ. \tag{3-2-a}$$

There are two high tides which can generate power per day, and hence the total energy per day is 160GJ. Mean power generation is therefore given by:

$$P_{av} = \frac{E_p}{t} \tag{3-5}$$

This amounts to 1.85MW of power generated on average. This assumes that the generator operates for 24 hours. However, the generator operates only on the high tides, which happen twice per day, so the actual generation when the generator operates is 12.9MW.

Table 3-1 The barrage parameters

Parameter	Value	Units
Basin area	7 065 600	m^2
High tide	2.01	m
Low tide	0.21	m
Tidal range	1.8	m
Tidal period	12.42	Hour
Floor rate	147.2	m^3/s

3.4 Selection and design of the tidal current turbine

The tidal turbine operates at low head and, according to the turbine application chart in Figure 3-1 adopted from [50], the Kaplan and the bulb turbines are ideal for the generation plant. The turbine rate head according to [50] is given by:

$$H_r = 0.66 \text{ x Mean Tidal range} = 0.66 \text{ x } 1.5 = 0.99 \approx 1\text{m} \quad (3\text{-}6)$$

This leaves the bulb turbine as the turbine of choice for the tidal barrage power plant. The chart estimates a power output of 1.5 to 2MW for the turbine. This implies that the barrage can employ 5 turbines to generate the required 10MW.

The runner diameter for the 2MW turbine is then given by:

$$D_t = K_1 {Q_d}^{0.473} \quad (3\text{-}7)$$

Where K_1 is a constant equal to 0.41 for the runner diameter greater than 1.8m, and Q_d is the discharge in m^3/s.

The turbine runner diameter for the design is, therefore:

$$D_t = 0.41 \times 147.2^{0.473} = 4.3\text{m} \quad (3.7\text{-a})$$

For design, a runner diameter of 4.3m can be used.

The rotational speed for the turbine is given by:

$$n = \frac{Q^{0.5}}{H^{-0.75}} = \frac{73.6^{0.5}}{1.5^{-0.75}} = 11.6 \text{ rpm.} \tag{3-8}$$

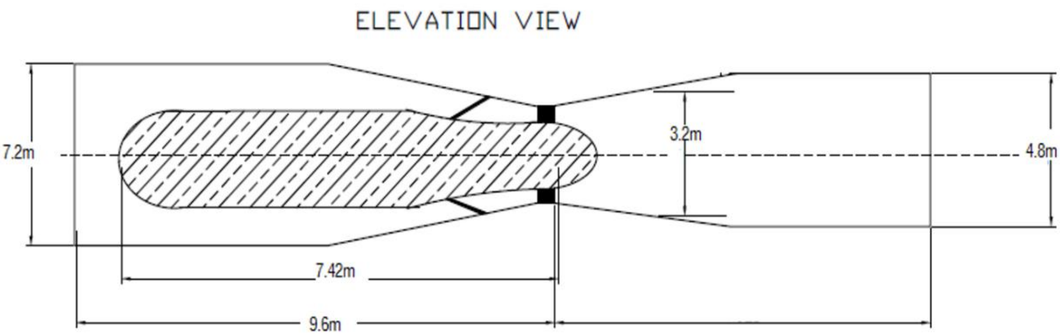
Using a synchronous generator, it implies that the number of poles requires:

$$p = \frac{120 \times 50}{11.6} = 517 \text{ poles.} \tag{3-9}$$

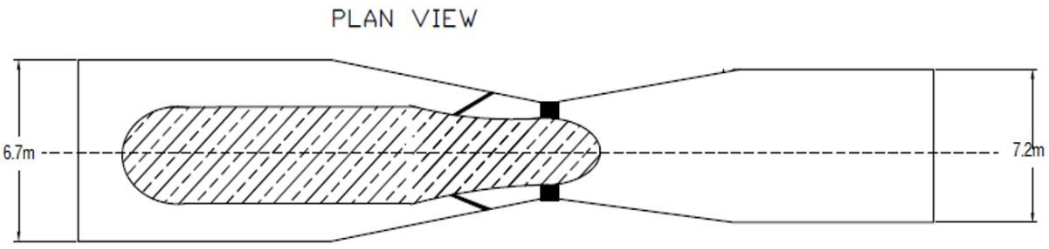
According to [53], the tip-speed ration, λ, for a marine turbine with three blades or more should be equal to four (4). For a turbine running at 1.2 rad/s, with a rotor radius of 2.17m, then it implies that the minimum water velocity for power generation is:

$$V_{min} = \frac{2.17 \times 1.2}{4} = 0.65 \text{m/s} \tag{3-10}$$

From the dimensioning proposed in [50], the channel for the placement of the turbine in the barrage can be determined based on the calculated runner diameter. Figure 3-3 shows the elevation and plan view of the turbine in the channel. The dimensions are based on the runner diameter, which in this design is 4.3m. The minimum width of the barrage is 25m to accommodate the turbine. For maximum power extraction, a turbine with pitch control can be used. The control mechanism is not core to this design.



(a)



(b)

Figure 3-3 (a) Elevation and (b) plan view of the turbine in the barrage.

Figure 3-4 shows the section through the turbine that has to be mounted in the tidal barrage generation channel and the different components of the turbine.

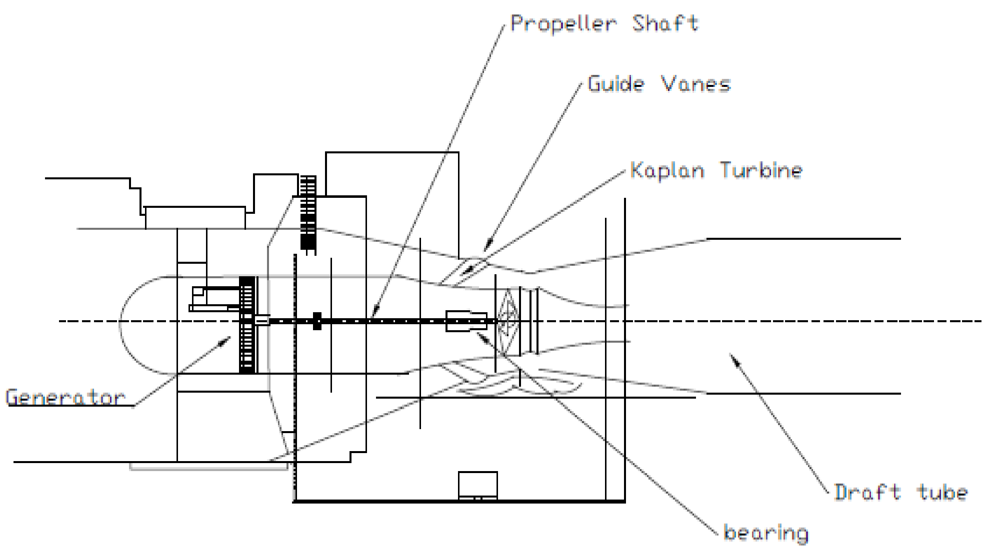


Figure 3-4 Labelled bulb turbine and generator mounted in the barrage channel.

Figure 3-5 shows the structural view of the generator that forms part of the turbine. The diagram is a cut through the generator component, which will be enclosed in the nacelle.

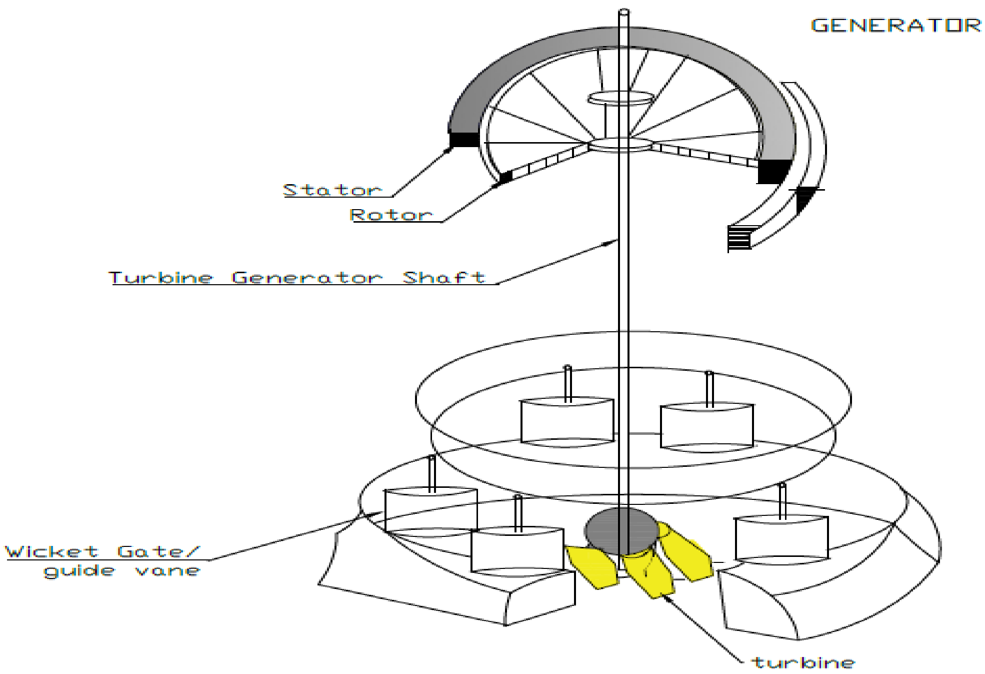


Figure 3-5 Section through the internal structure of the generator

There are several methodologies used in designing the tidal current turbine. The important points to take into consideration include the conditions of operation, the designed power output, as well as the cut in and cut off speeds, among other things. The design can follow the wind turbine design, but a marine turbine is exposed to more significant stress due to the high density of seawater [53]. The swept area determines the amount of energy that the turbine can capture. For this design, five 2MW turbines are required. Table 3-2 shows the turbine design parameters deduced from the calculations.

Table 3-2 Tidal turbine design parameters

Parameter	Value	Units
Rotor diameter	4.3	m
Number of blades	3	
Hub height	2.6	m
Tip-speed ratio	4	
Pitch angle	variable	
Nacelle length	8	m
Generator type	PMSG	
Rated power	2	MW
Output type	3	Phase
Cut in speed	0.7	m/s
Rated speed	2.25	m/s
Cut out speed	5.5	m/s
C_p	0.45	

3.5 Design of the tidal barrage generation plant

The barrage for the 10MW system can be designed to have a number of generating units. The hydrodynamics of having an array of generating systems dictate a minimum-allowed separation between the generating units so that they do not interfere with each other. This is also a function of the size of the turbine blades. The optimum distance of separation of the turbines is three times the runner diameter [47]. The minimum length of the barrage is, therefore, at least 184m for a generating plant using five turbines of less than or equal to 3.6m diameter.

Figure 3-6 shows the design layout of the five turbines in the barrage. This arrangement has been adopted for simulations using the DTOcean® software presented in Chapter Four.

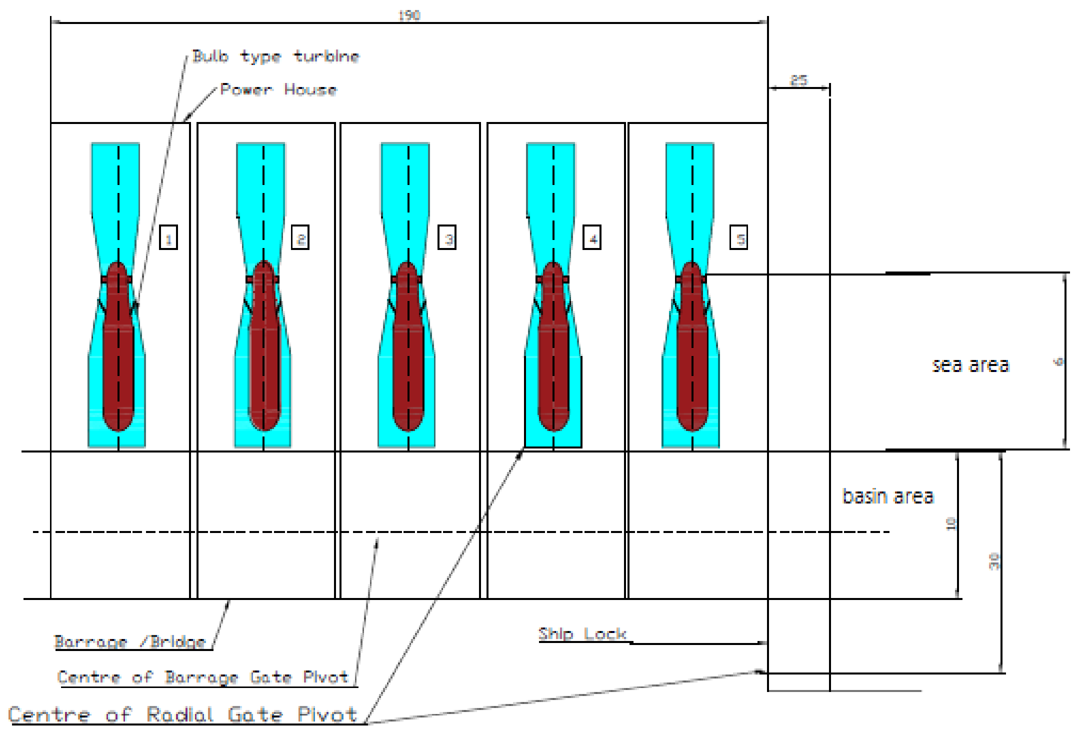


Figure 3-6 Arrangements of turbines in the barrage

Using the calculated 4.3m runner diameter, the minimum depth to install a turbine should be enough to avoid cavitation and icing at the surface [53]. A depth at least equal to the runner diameter would be sufficient to enable the above. Resultantly, for a 4.3m diameter runner, it should be placed at least 3m below the minimum water level. Theoretically, this increases the potential energy available at the turbine blade. This requirement also means that more massive sluice gates are required to control the flow.

Figure 3-7 shows a section through the tidal barrage structure. The focus of the figure is the placement of the generator and the sluice gates, which control water movement during the high and low tide for power generation. The figure also shows that there is always a need for an access shaft to the generator. For the design, a 2MW generator is used, and there is an array of five generators for the 10MW installation.

The concrete walls provide the damming mechanism and are solid, except at the channels where the turbines are installed. Motorised automated sluice gates open and close to allow the flow of water in and out of the basin. The minimum height of the sluice gates should be at least a metre higher than the turbine rotor diameter. The channels leave space for connecting the cables to carry power to the land for further transmission. Table 3-3 shows the design parameters for the tidal barrage power plant.

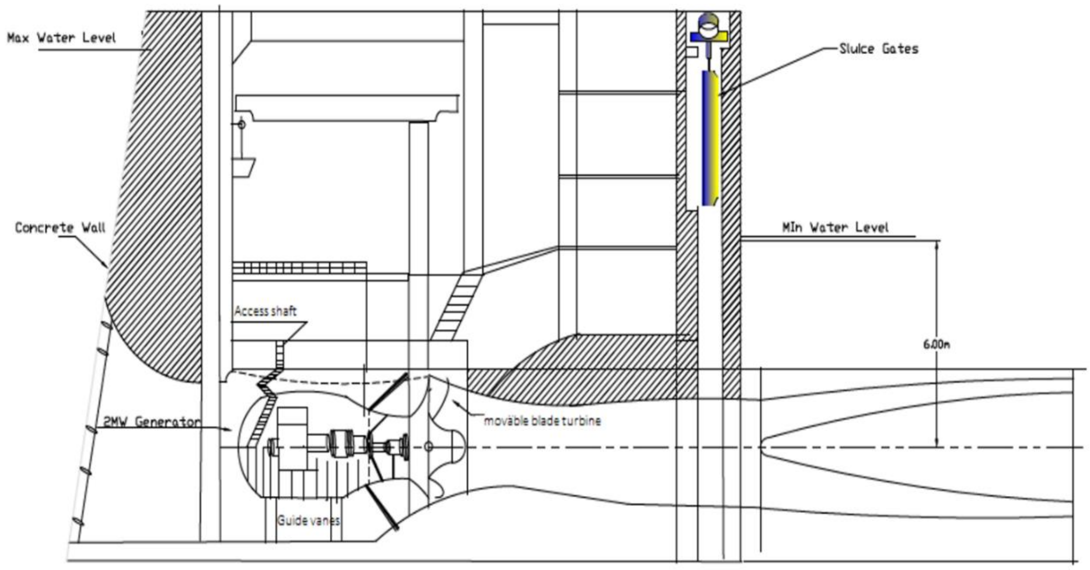


Figure 3-7 Section through the tidal barrage generator channel showing the positioning of generating unit and power connecting corridor.

Table 3-3 Tidal barrage power plant design parameters

Component	Value	Units
Damming wall length	190	m
Barrage depth	10	m
Width of barrage wall	25	m
Channel width	30	m
Basin area	706 560	m^2
Water head	6	m
Number of turbines	5	

3.6 Conclusion

The design of the tidal barrage power plant has been presented in this chapter. Observations indicate that the tidal range is particularly influential in site selection, with the discharge rate determining the amount of energy that can be captured by the system. The discharge rate also determines the required rotor diameter, which in turn influences the physical size of the barrage. The tidal barrage design parameters show that the plant has the potential to generate 12MW. The energy generated per day is 160GJ, which translates to approximately 16GWhr per annum. The available CAD drawings have been presented in the appendices to give a visual impression of the design. Chapter Four is a presentation of the simulation of the design and the results compared with the calculated values.

CHAPTER FOUR

SIMULATION OF THE TIDAL BARRAGE SYSTEM

4.1 Introduction

The tidal barrage system has been modelled in Chapter Three. The potential power generation of the tidal barrage system has been estimated using an analytical method. This chapter presents the simulation of the tidal barrage system. The Matlab®/Simulink® is very useful in modelling and simulating electrical power systems. The modelling equations are derived from the physics of the given components. In this chapter, the simulation of the tidal plant components, as well as the whole power plants, electrical behaviour is presented. The electromechanical system is also simulated using DTOcean® software to quantify the power generation of the system. A comparison of the two simulation results is also presented. The whole tidal power plant can be modelled using the block diagram presented by [42] and [55] shown in Figure 4-1.

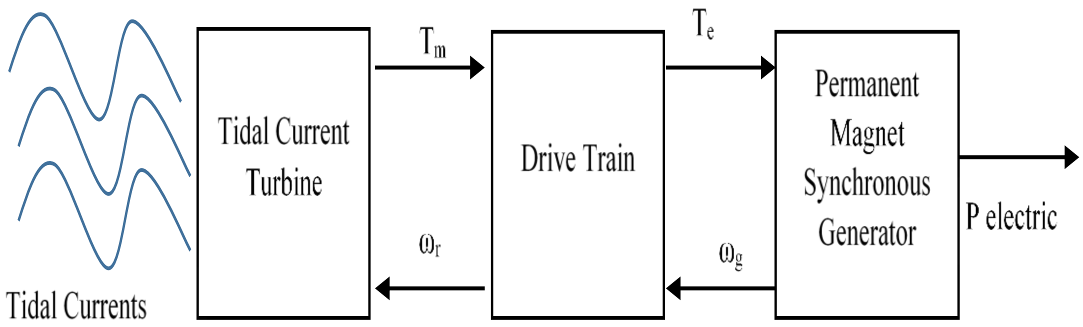


Figure 4-1 Block diagram of a tidal energy plant [47, 48].

4.2 Tidal current Simulink® model

Current velocity can model the tidal current, where the velocity profile is first assumed to follow a sinusoidal characteristic. This enables the handling of the harmonics involved, and these can give an accurate model for the tidal current. The two principle harmonics are the principle semi-diurnal harmonic M_2, and the principle diurnal solar harmonic S_2.

M_2 has a period of approximately 12.5 hours, while S_2 has a period of 12 hours. The spring tide is when the harmonics tend to reinforce each other, and the neap tide is when the harmonics tend to cancel each other out. Table 4-1 shows the basic spring-neap cycles produced by M_2 and S_2.

There are several mathematical models for modelling the tidal velocity. One expression depends on the tide coefficient and independent spring and neap velocities [54].

$$\boldsymbol{v_{tide}} = \boldsymbol{v_{nt}} + \frac{(\boldsymbol{C}-\boldsymbol{C_{neap}})(\boldsymbol{v_{st}}-\boldsymbol{v_{nt}})}{\boldsymbol{C_{spring}}-\boldsymbol{C_{neap}}} \tag{4-1}$$

Where $\boldsymbol{v_{tide}}$ is the tide velocity, $\boldsymbol{C_{spring}}$ and $\boldsymbol{C_{neap}}$ are the spring tide medium and neap tide medium coefficient respectively, $\boldsymbol{v_{st}}$ and $\boldsymbol{v_{nt}}$ are the spring tide velocity and the neap tide velocity, respectively. C is the overall tide coefficient.

The model requires measured spring tide and neap tide parameters for a specific site.

The other common model considers the tidal current speed as a sinusoidal function of tidal current magnitude A_i, tidal period T, and harmonic phase P_i [54].

$$A_{(t)} = \sum A_i sin(2\pi f_i + P_i) \tag{4-2}$$

The model takes cognisance of the different harmonic components, and each component is defined by its angular frequency in solar hours.

The tidal current is modelled for Matlab®/Simulink® using the later expression in A(t).

From data presented in [55] and [56], the constituents of the tidal currents in Durban are given in the table, measured over a 37-year period until 2018. SD is for semi-diurnal constituents, and D is for diurnal constituents. The four constituents with all data available are used in the simulation.

Table 4-1 Durban tidal constituents characteristic values [55,56]

Constituent	Amplitude (m)	Phase (ϴ)	Period (Hours)
M2 (Principle lunar)	0.561	43.77	12.42
S2 (Principle Solar-SD)	0.3377	77.53	12.00
O1 (Principle Lunar-D)	0.016	298.47	25.82
K1 (Lunisolar Declination- D)	0.052	145.71	23.93
K2 (Lunisolar Declination –SD)			11.97
P1 (Principle Solar-D)			24.07

Using the model from [48] which presents the harmonic components of the tidal waves using measured values, the model in Figure 4-2 as been used with the variation that, in this model, only four components have complete data and hence are used in the simulation model.

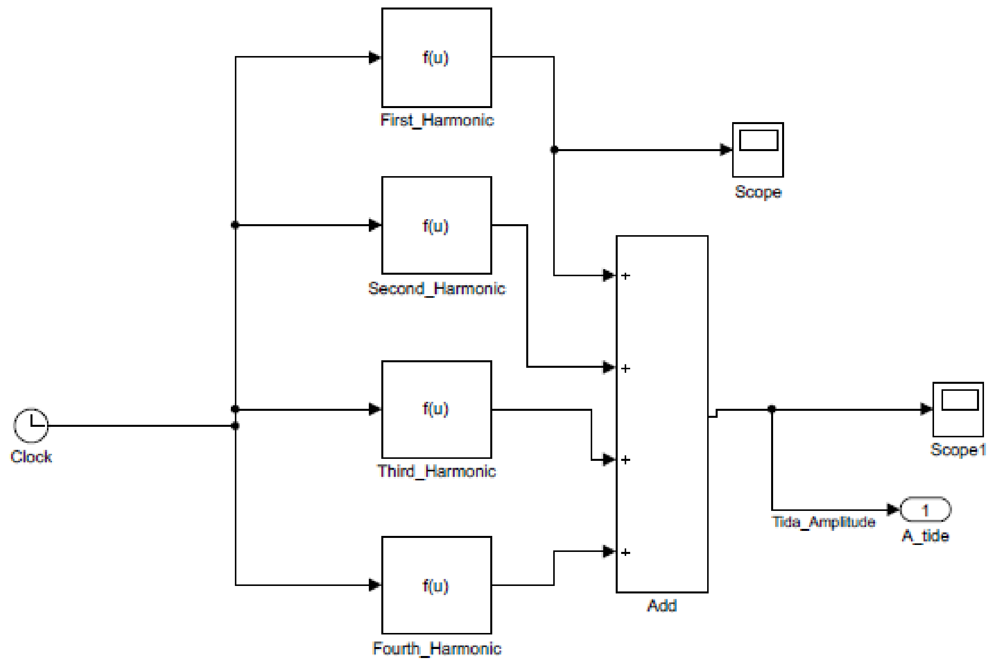


Figure 4-2 Tidal current magnitude simulation model [48].

The simulation results in Figure 4-3 and Figure 4-4 show the first tidal harmonic and tidal current amplitude pattern, produced by the four harmonic components, respectively. The tidal range for the waveform is approximately 1.6m from the simulation.

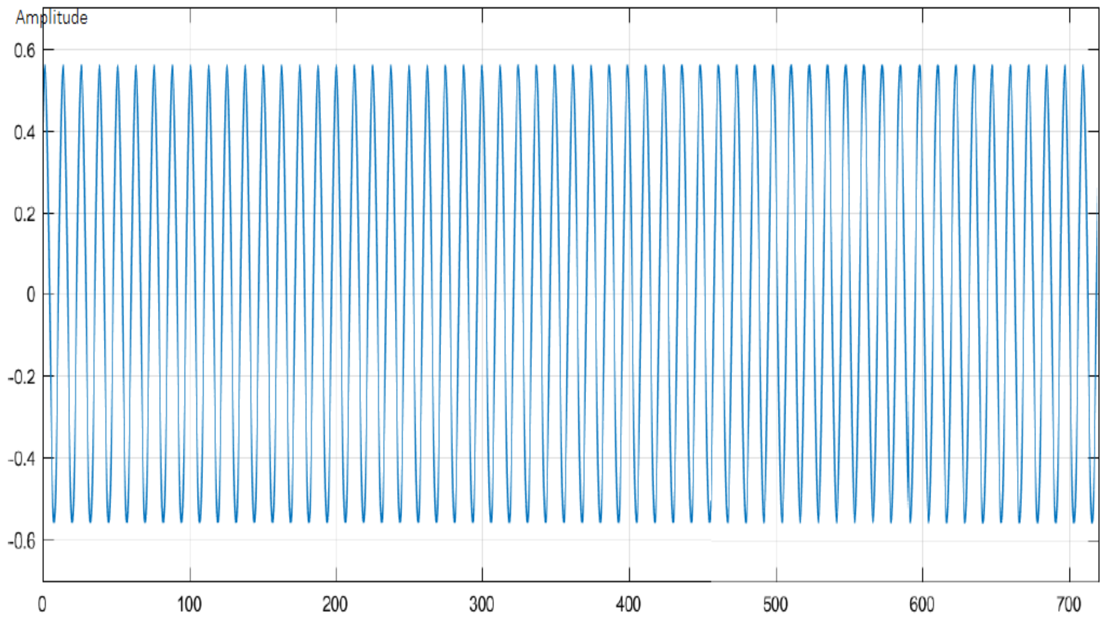


Figure 4-3 Tidal current first harmonic.

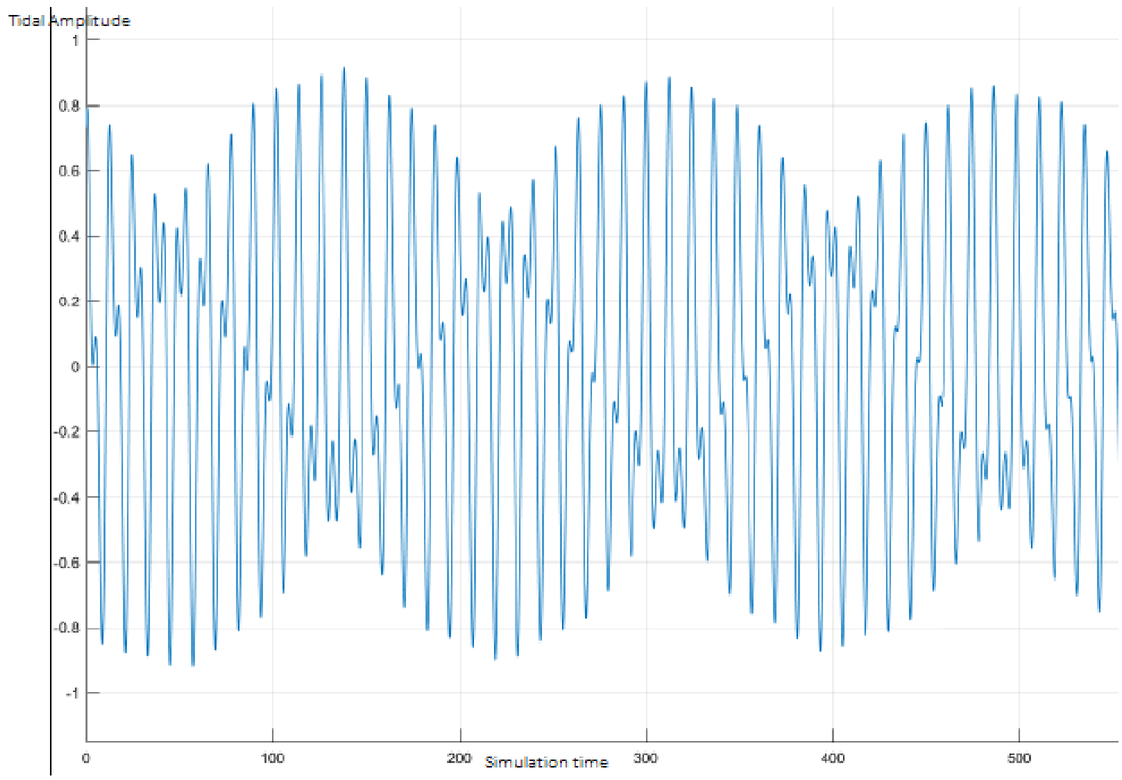


Figure 4-4 Seven-day tide current simulation results

4.3 Tidal current-turbine Simulink® model

The model equations in section 2.10 of Chapter Two are used to produce the Matlab® model for the tidal current turbine. The tidal current velocity is assumed to follow a sinusoidal cycle for the block simulation with amplitude 1.5. The generator speed is assumed to increase to synchronous, and remain there for the duration of the generation cycle.

The rated speed is 2m/s and this translates to 1.25rad/s for a 3.2m rotor diameter. This translates to a rotational speed of 11.9rpm for a 3.2m rotor diameter.

The rotor diameter is assumed to be 3.2m for simulation purposes as determined in Chapter Three. Figure 4-5 shows the developed simulation model. The model uses the inertia and frictional coefficient as the main determining parameters in getting the developed mechanical torque of the system.

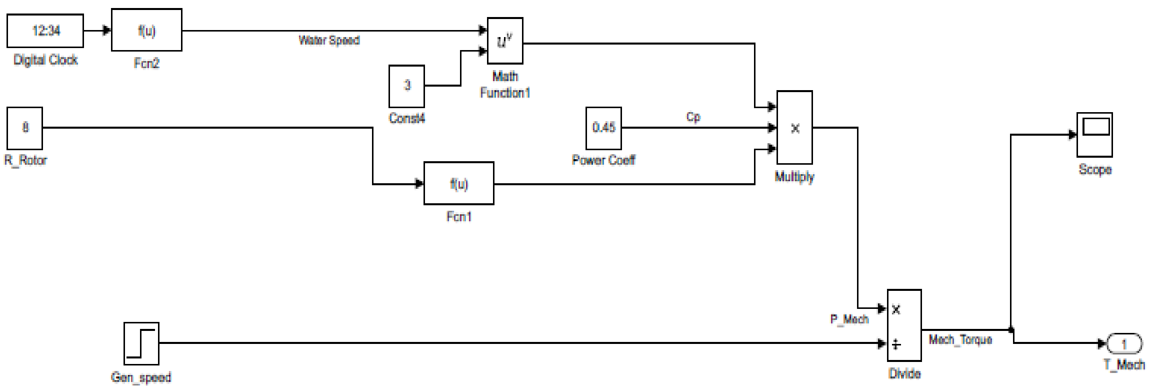


Figure 4-5 Tidal current turbine simulation model

Using the given parameters and simulating for a one-week period, the mechanical torque pattern shown in Figure 4-6 was observed. It shows that the tide sometimes becomes low and cannot develop enough torque to move the turbine.

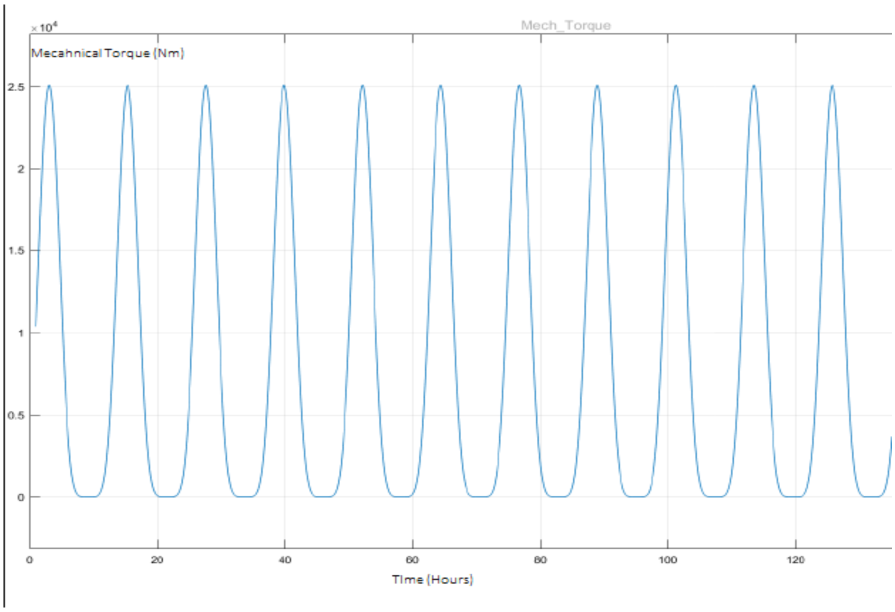


Figure 4-6 Mechanical torque from the turbine

4.4 System drive train Simulink® model

The drive train coupling includes the turbine and generator mass components. These can be modelled by relating them to the mechanical torque of the system [57].

$$J\frac{d\omega_g}{dt} = T_{mech} - T_{elect} - \beta_{eq}\omega_g \tag{4-3}$$

J is the combined coefficient of inertia for the turbine and the generator, while β_{eq} is the damping ratio. Using Laplace transforms [57]:

$$Js\omega_{g(s)} = T_{mech}(s) - T_{elect}(s) - \beta_{eq}\omega_g(s) \tag{4-4}$$

$$\omega_{g(s)} = [T_{mech}(s) - T_{elect}(s)]\, x \frac{1}{Js+\beta_{eq}} \tag{4-5}$$

Integrating the expression with respect of time [57]:

$$\omega_g = \frac{\int(T_{mech}-T_{elect})dt - \int \beta_{eq}\omega_g dt}{\int Jdt} \tag{4-6}$$

The drive train can either be represented as a Laplace transfer or as a time domain expression. The transfer function block is shown. The mechanical torque and the electrical torque can be represented by an exponent of a sine wave for block simulation with a phase shift. The values of J and β_{eq} are not available and have been assumed to be 3500 and 500 respectively for simulation. The block is, however, implemented internally in the PMSG Simulink® inbuilt model. The simulation demonstrates how the generator speed responds to change in torque.

Figure 4-7 shows the mechanical simulation model. The model was simulated independent of the generator but the parameters are used in simulating the generator.

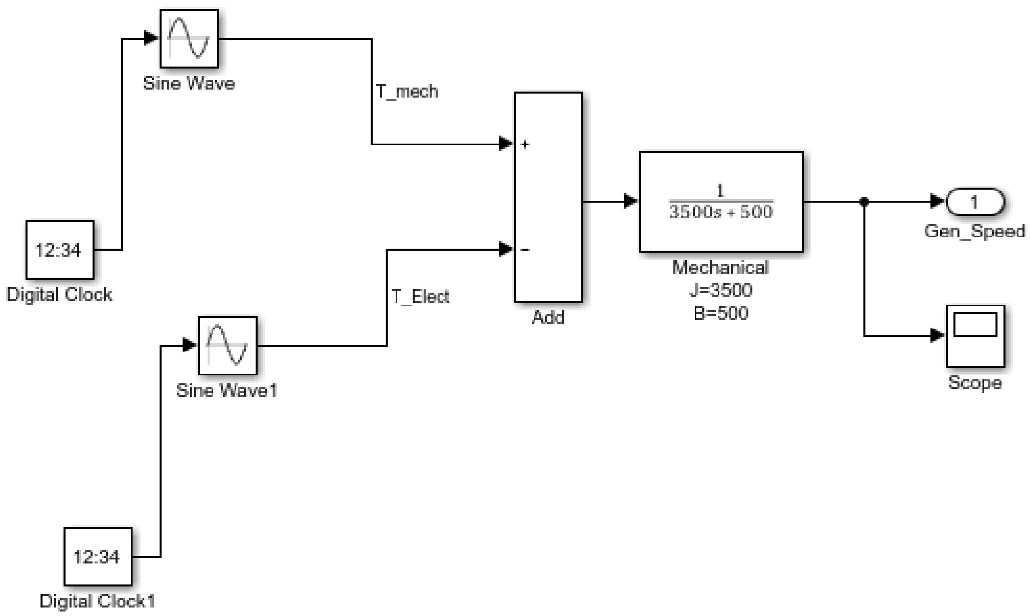


Figure 4-7 Mechanical simulation model

Figure 4-8 shows the variation of generator speed with mechanical and electrical torque. The generator speed also varies with the tidal amplitude as expected.

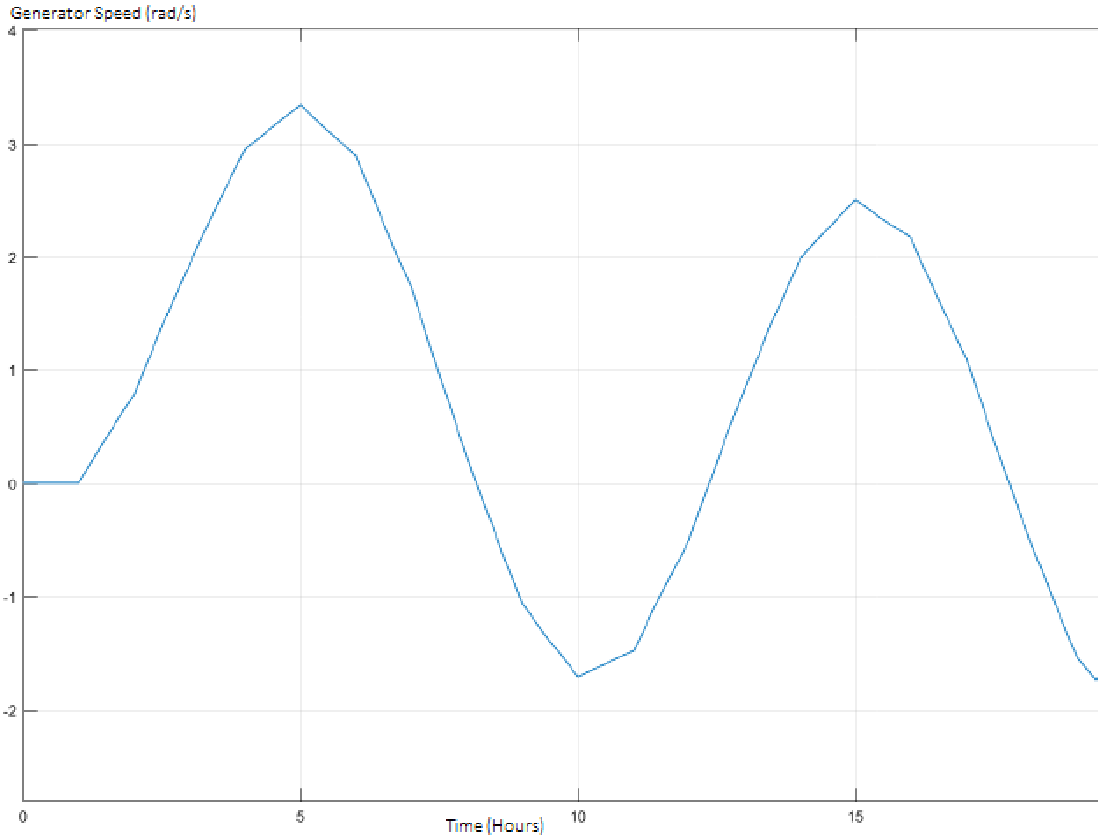


Figure 4- 8 Simulated response of generator speed to electrical and mechanical torque

The drive train indicates the relationship between the generator speed, the electrical torque, and the mechanical torque. The equation gives the expression for electric torque in the d-q frame. This is included in the inbuilt generator model [57].

$$T_e = \frac{3}{2} P[\left(L_q - L_d\right) I_d I_q + \varphi_{pm} I_q \qquad (4\text{-}7)$$

4.5 Permanent Magnet Synchronous Generator Simulink® model

The generator model is simplified by using Laplace transforms since the required outputs for calculating electrical torque are I_d and $I_{q.}$

The d-components of voltage and the current are given as [58]:

$$V_d(s) = -L_q I_q W_e(s) + L_d s I_d(s) + R I_d(s) \qquad (4\text{-}8)$$

$$I_d(s) = \frac{V_d(s) + L_q I_q W_e(s)}{(L_d s + R)} \qquad (4\text{-}9)$$

The q-components of the voltage and current are given as [58]:

$$V_q(s) = -L_d I_d W_e(s) + L_q s I_q(s) + R I_q(s) + \varphi_{pm} W_e(s) \qquad (4\text{-}10)$$

$$I_q(s) = \frac{V_q(s) + (L_d I_d - \varphi_{pm}) W_e(s)}{(L_q s + R)} \qquad (4\text{-}11)$$

The flux components are given by [58]:

$$\varphi_d = L_d I_d + \varphi_{pm} \qquad (4\text{-}12)$$

$$\varphi_q = L_q I_q \qquad (4\text{-}13)$$

$$W_e = P\ W_g \qquad (4\text{-}14)$$

However, Simulink® has a Permanent Magnet Synchronous Machine which can be configured using machine parameters for the simulation. The model in Figure 4-9 is used for simulations.

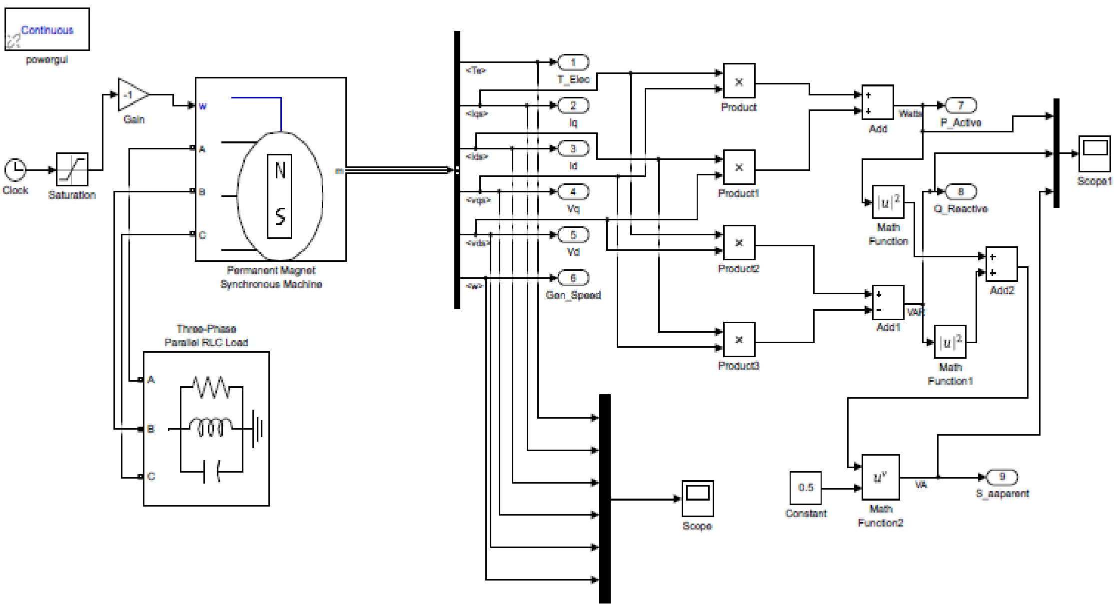


Figure 4-9 Permanent magnet synchronous generator model

4.6 Power output modelling from generator outputs

The electrical power output is a function of the d-q parameters of current and voltage.

The active power, P is given by [58]:

$$P = V_d I_d + V_q I_q \qquad (4\text{-}15)$$

The reactive power, Q is given by [58]:

$$Q = V_d I_q - V_q I_d \qquad (4\text{-}16)$$

From the above, the apparent power, S - which gives the KVA generator rating - can be calculated using [58]:

$$S = \sqrt{P^2 + Q^2} \qquad (4\text{-}17)$$

4.7 Tidal barrage power plant simulation using Simulink®

The independent blocks are combined as sub-systems to give the full power plant. The simulation results show how the generated power changes with the tidal current magnitude. Figure 4-10 shows the simulation model for the whole power plant as an interconnection of the independent sub-systems.

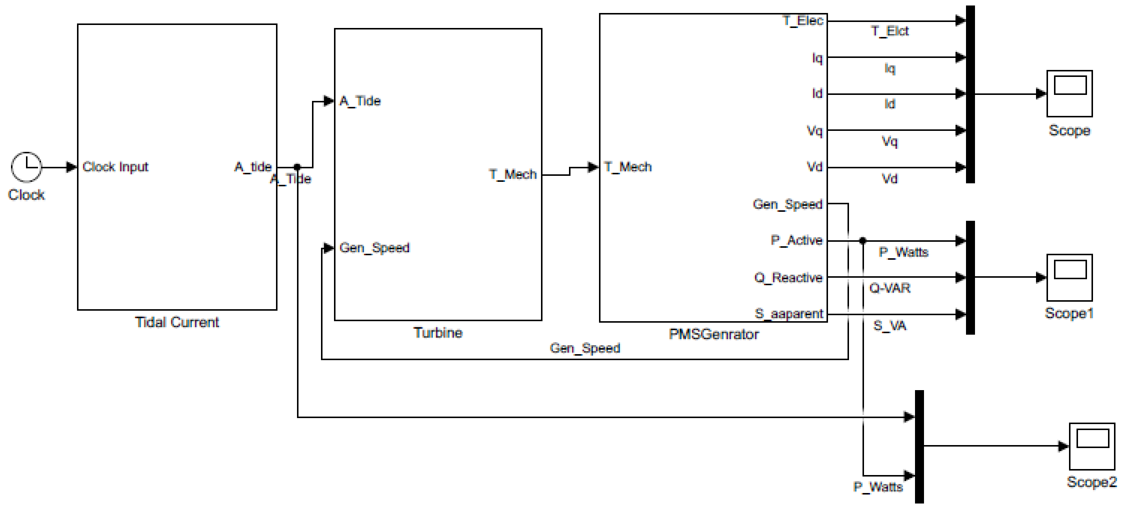


Figure 4-10 Tidal power plant simulation model

Figure 4-11 shows the d-q current and voltage components of the power developed by the generator, and Figure 4-12 shows the active, reactive, and apparent power developed from the PMSG.

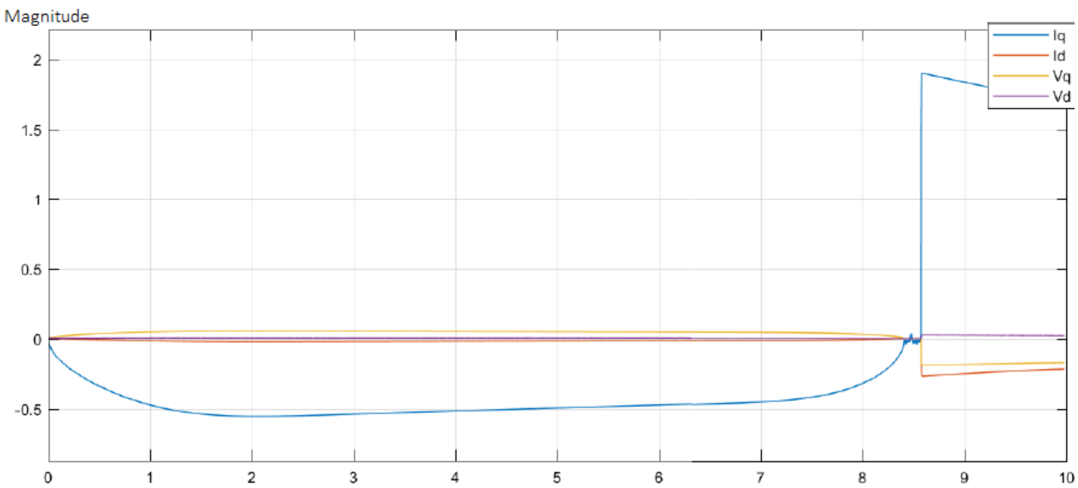


Figure 4-11 D-Q components of voltage and current for developed power

The simulation results in Figure 4-12 show the observed power developed from the system. The type of load determines the power factor of the system. The rated power is the apparent power, S, which is almost equal to the real active power as shown.

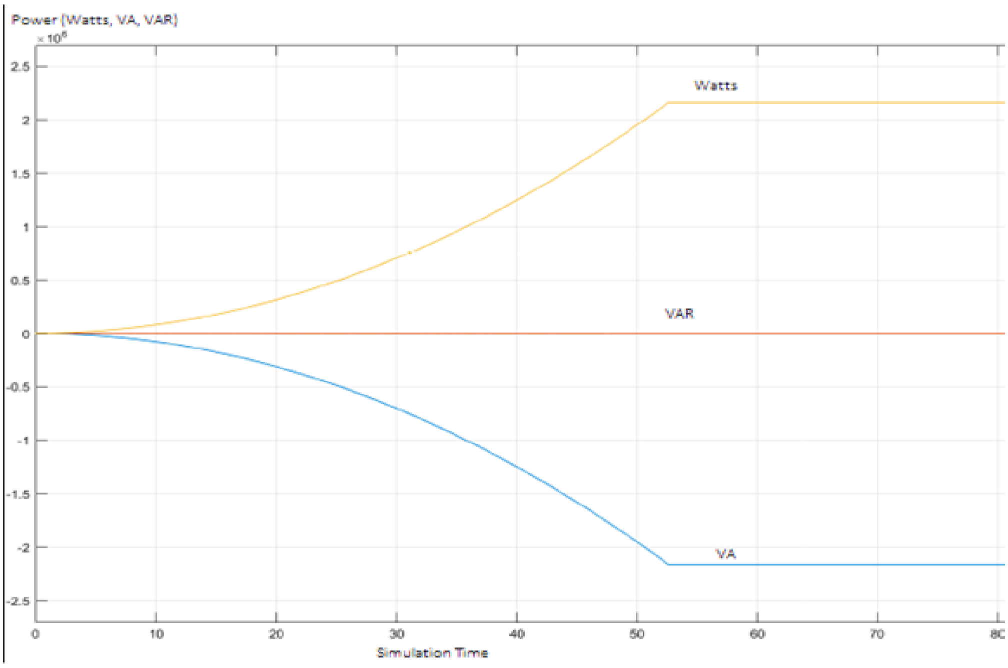


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Figure 4-12 Simulated power output from generator

The simulation, using given parameters, show a generation of 2.2MW per unit. Assuming that the unit operates for four hours per day, then the generation per annum for the array is given by:

$$\boldsymbol{Total\ Energy = 5 \times 2.2 \times 10^{6} \times 4 \times 365 = 16GWhr\ per\ annum}$$

4.8 Simulation of a designed power plant using DTOcean®

The power plant array components have been designed and dimensioned using AutoCAD®. The design parameters are used to observe the system performance using DTOcean® software. The DTOcean® software has several modules that are used to aid in the design, development, environmental, and economic planning. This project is mainly concerned with the design of the barrage power plant; hence, the hydrodynamics and the electrical sub-system modules will be used in the simulation.

The design in Chapter Three revealed that the barrage requires a horizontal area of 706 560m^2. The lease area is, therefore, greater than the horizontal water surface area. The barrage generation channel per turbine covers 400m^2. This gives an additional 2000m^2 for the five turbines. Therefore, the lease area can be approximated to 710 000m^{2,} excluding the cable area. The data requirements for running the simulation was guided by literature in [59].

The tidal device model used is illustrated in Figure 4-13 using data presented in Chapter Three. A rectangular model is chosen for purposes of the simulation.

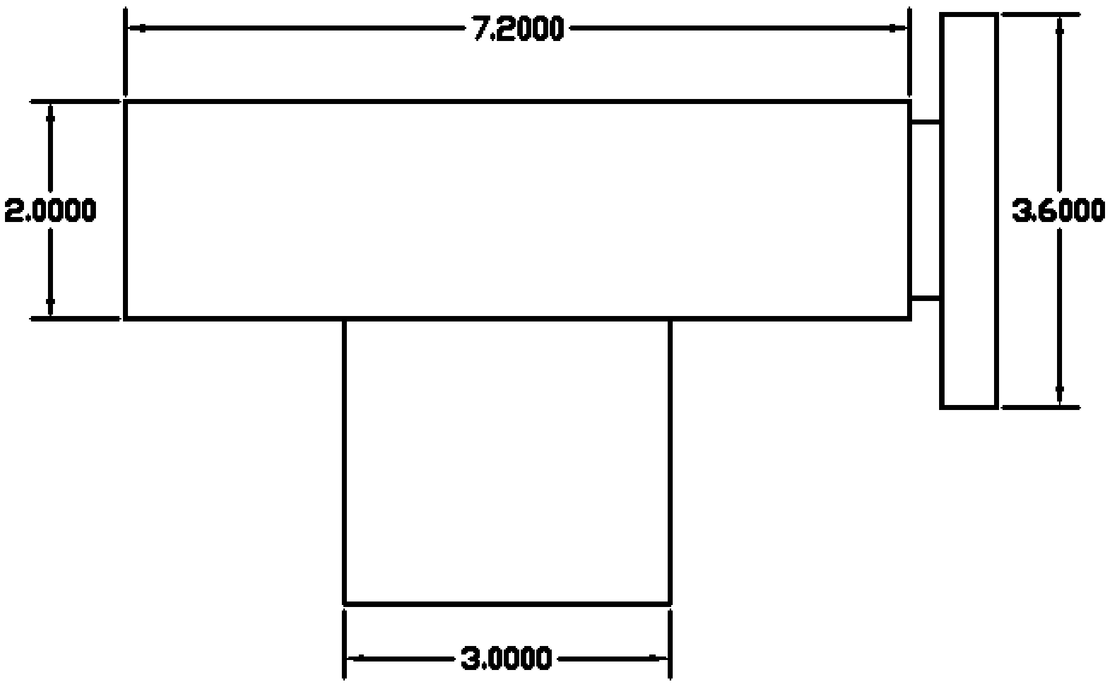

Figure 4-13 Tidal device model for analysis

The time series tidal data for Durban was not available. However, the available data from online sites was used as the model time series data for purposes of simulation. The data was extracted from [44] by observing the animated data.

Using the Wave Energy Converter (WEC) simulator, the tidal device hydrodynamics have been analysed. The available rectangular mesh was used for the analysis, which shows the behaviour of the fixed tidal device underwater. The mesh is used to analyse the forces acting on the device as a function of the tidal parameters. This is used by the simulator to determine the power generation. Figure 4-14 shows the tidal device mesh for the WEC simulator.

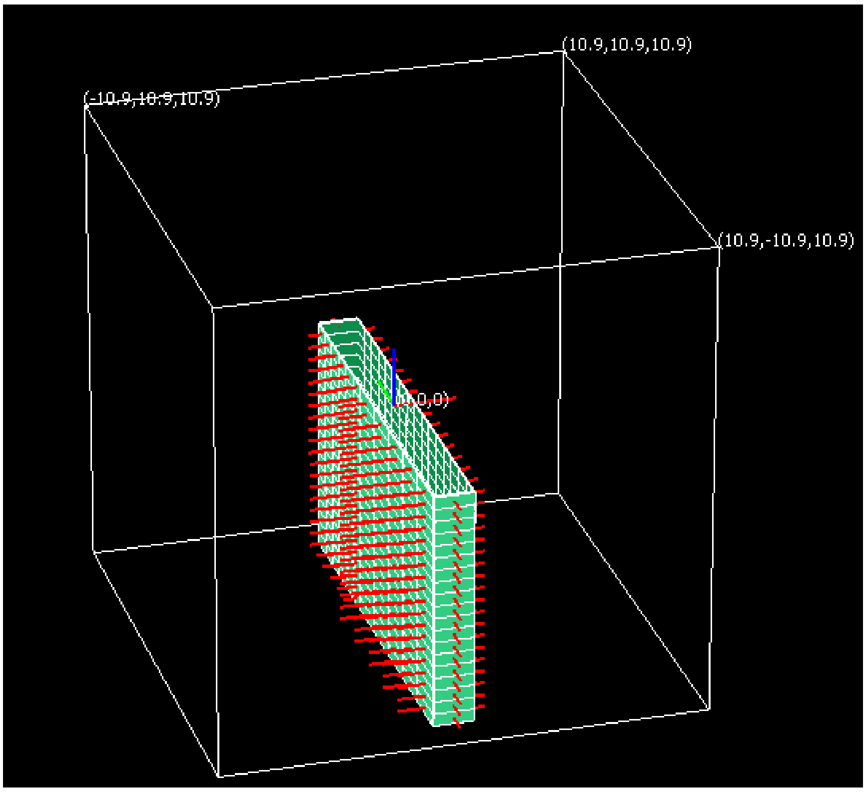

Figure 4-14 Tidal device mesh for WEC simulator

The WEC simulator consumes wave time-series data to evaluate the power generation. Figure 4-15 shows the tidal time series data that was used in the simulation.

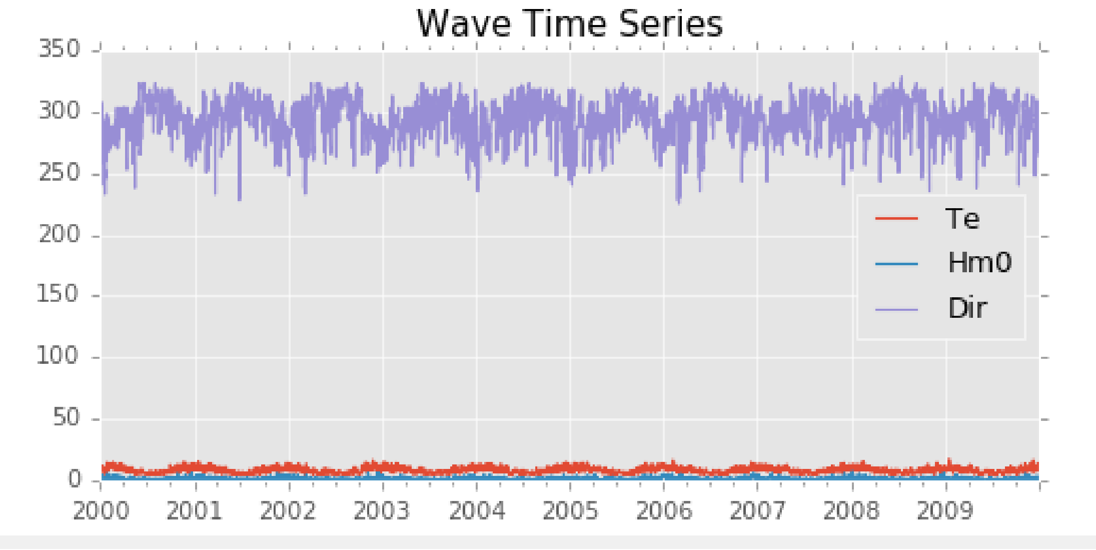

Figure 4-15 The tidal wave time series data

The resultant tidal velocity time series is shown in Figure 4-16. It can be observed that the velocity rarely reaches 1.5m/s, as observed in the Durban wavetables.

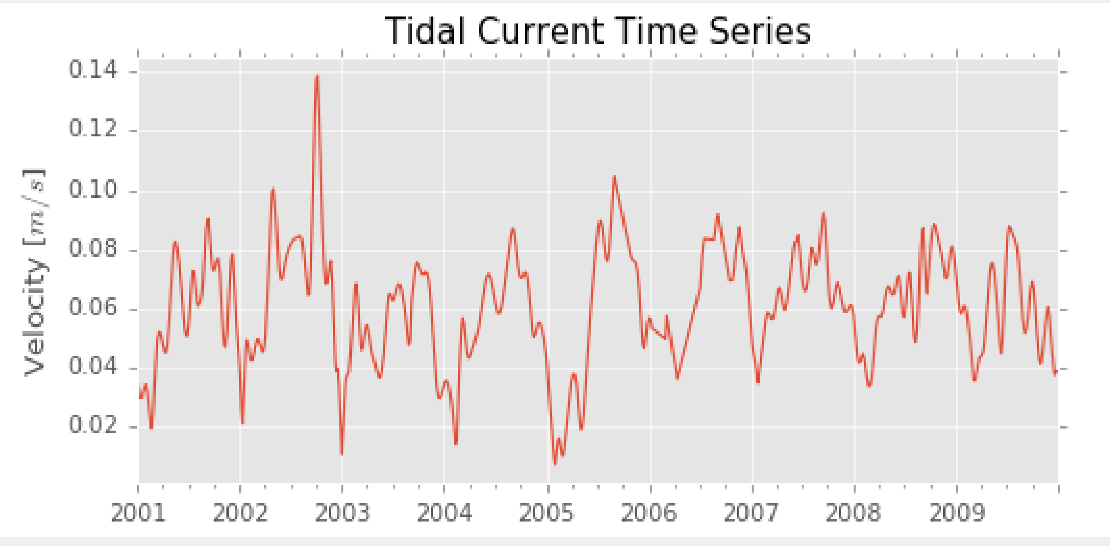

Figure 4-16 Tidal current velocity time series

The runner diameter designed to be 3.2m implies that the separation of the turbines should be at least five times the runner diameter. For the design lease area, Figure 3-14 shows the proposed layout of the devices in the lease area. The lease area was designed with reference to an arbitrary origin with coordinates (0, 0, 0). The coordinates show the lease area as designed for the barrage. The five devices are placed at the same depth and evenly spaced, as illustrated in Figure 4-17.

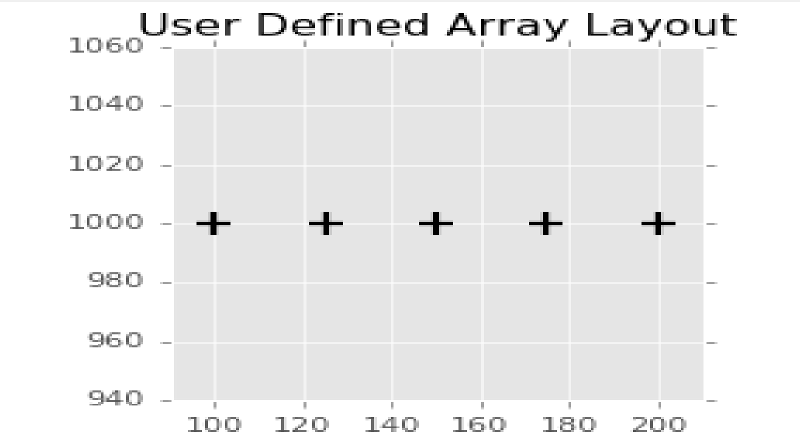

Figure 4-17 Array layout in the lease area

The device design shows that there are two interacting devices; the hub and the turbine. The hub is fixed to the flow, and the turbine is fixed to the hub with its rotating components. As the frequency increases, the damping coefficient increases from zero together with the added mass. As frequency becomes very large, the damping coefficient goes to zero, as expected, and the mass settles at a finite value. An operating point can, therefore, be selected from the results shown in Figure 4-18.

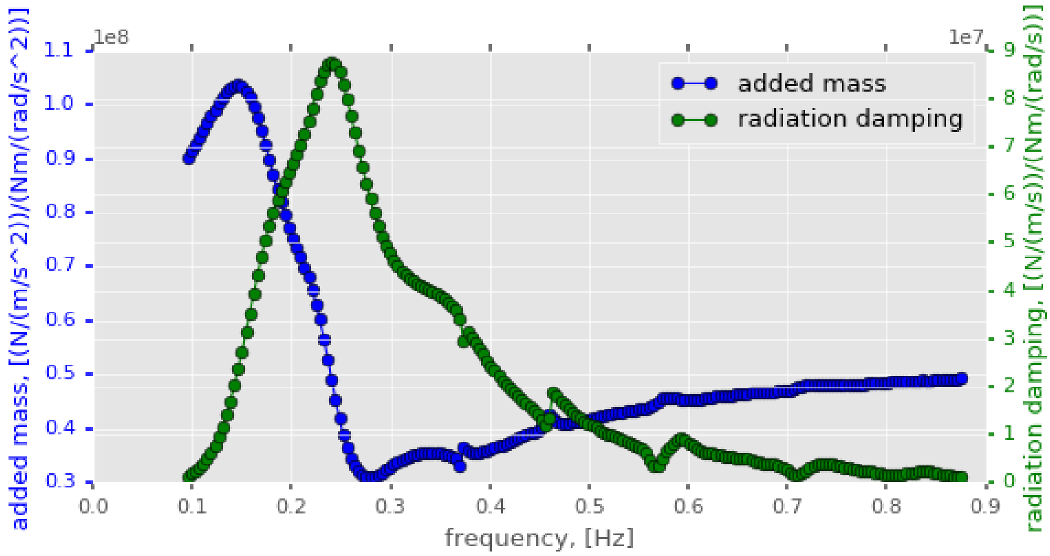

Figure 4-18 Radiation co-efficient and added mass frequency response

The excitation coefficient starts at a higher value at low frequencies and reduces again to zero as frequency becomes high. This shows the corresponding excitation required to work against the system inertia. Figure 4-19 shows the variations. As frequency increases, the two bodies, the hub, and the turbine, start to synchronise and the phase goes to zero.

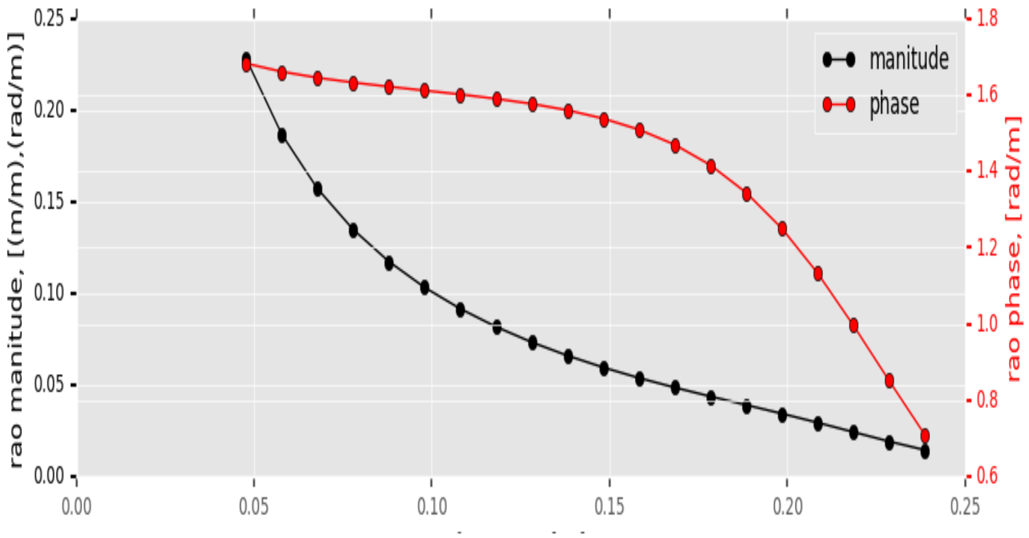

Figure 4-19 Excitation co-efficient magnitude and phase variation with frequency

The degrees of freedom in the turbine system is two, which includes the pitch and the yaw. The system mass is distributed, as shown in Figure 4-20.

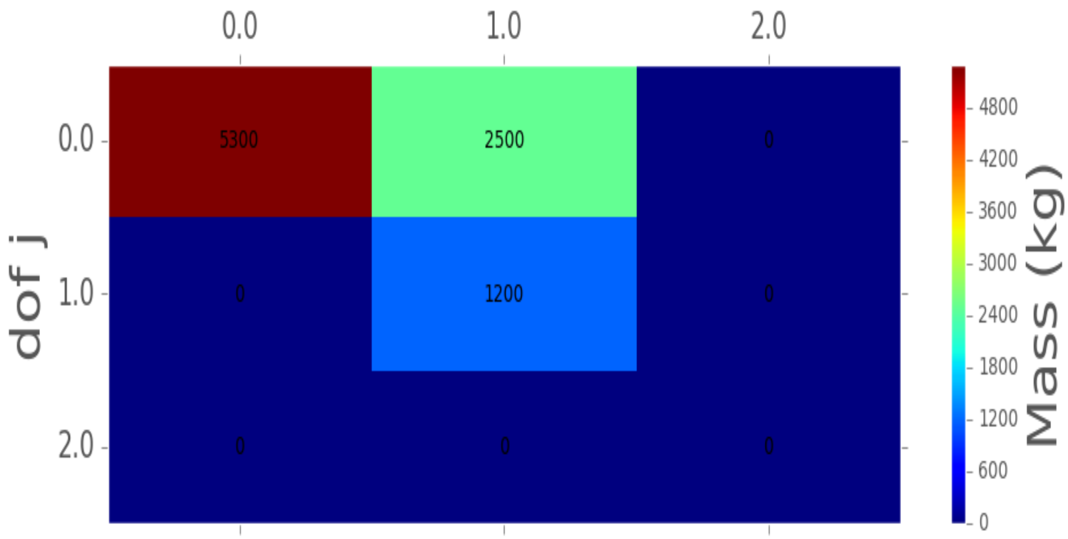

Figure 4-20 Tidal device mass matrix

The power developed by the turbine is a function of the water head, given here as the depth. The power matrix shown in Figure 4-21 shows that maximum power is at 8m depth, which corresponds to the design rated head for the turbine.

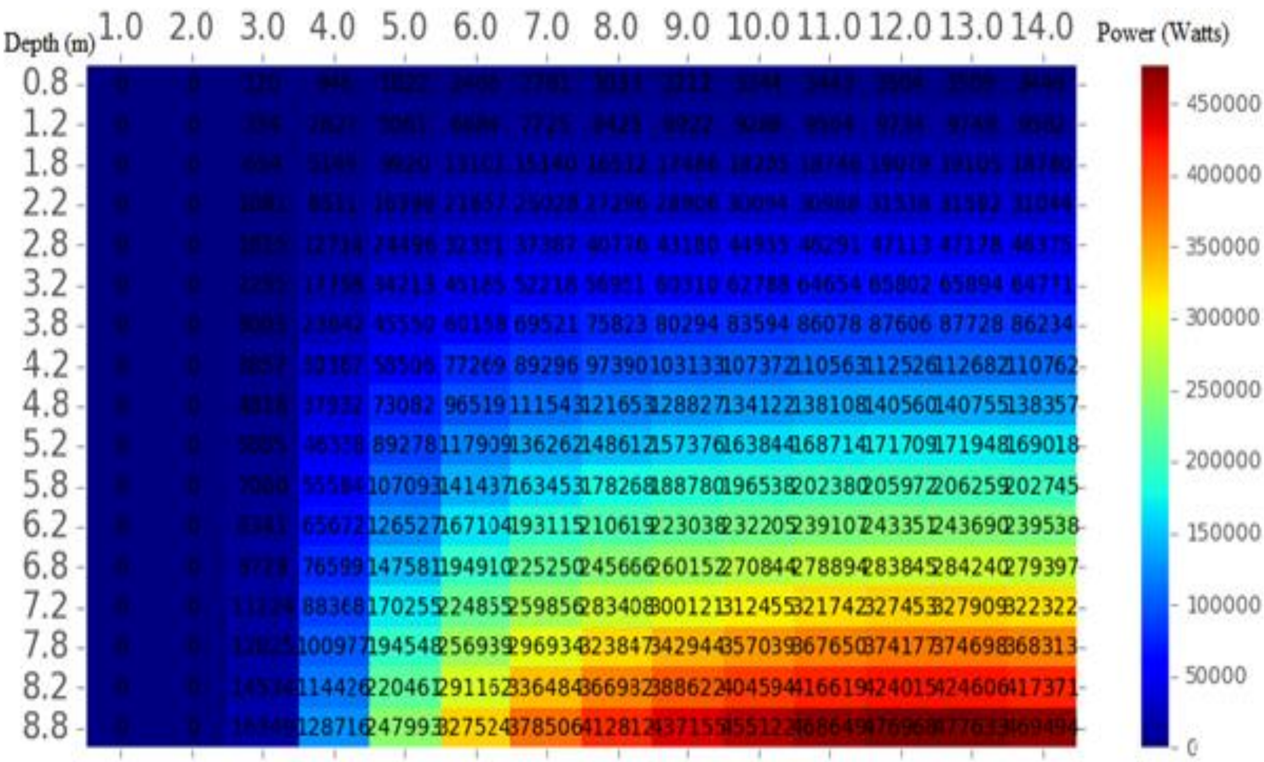

Figure 4-21 Turbine depth-power matrix simulation plot

The simulation gives the projected energy output. The results show that about 750MWhr can be harvested annually, per device, as shown in Figure 4-22. The power per device is less than the rated power as shown in Figure 4.23. The plant requires five generating turbine units, each producing 2MW. The units are numbered as device 001 to device 005.

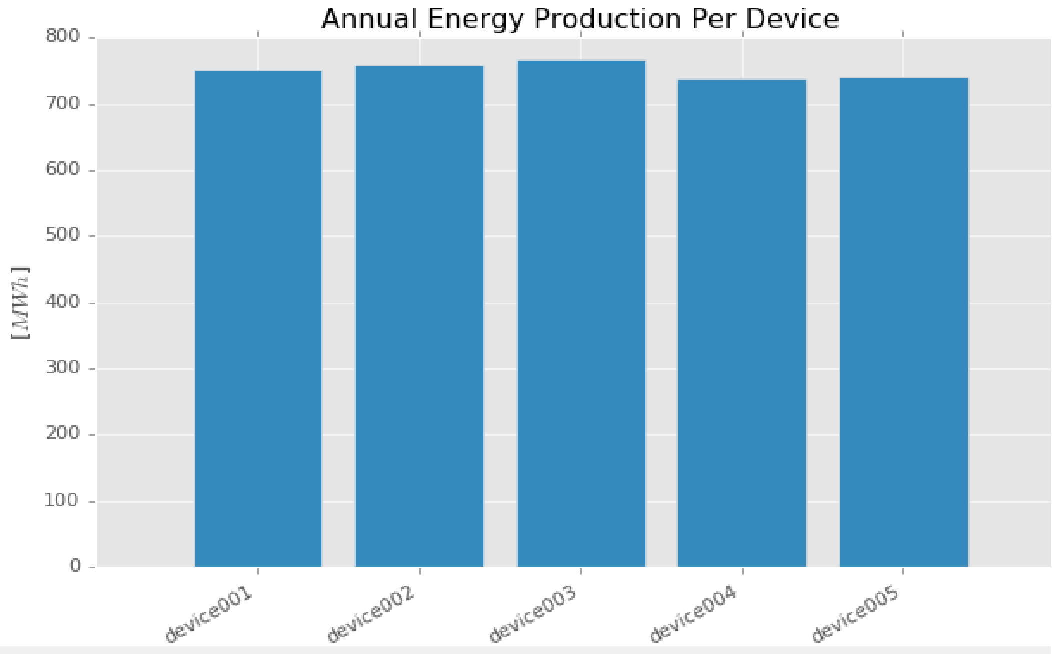

Figure 4-22 Projected energy per device per annum

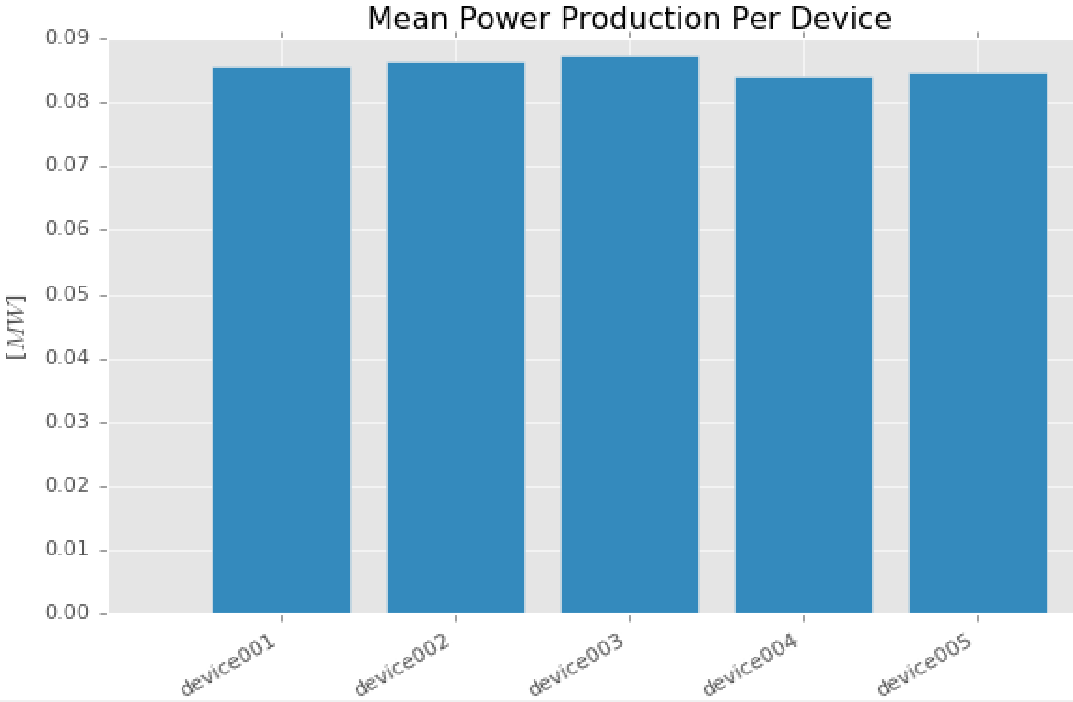

Figure 4-23 Mean power per device

Figure 4-24 is a mean power production histogram per device. The power matrix per device in Figure 4-25 is in agreement with the power production histogram, and maximum power is extracted close to the rated head depth.

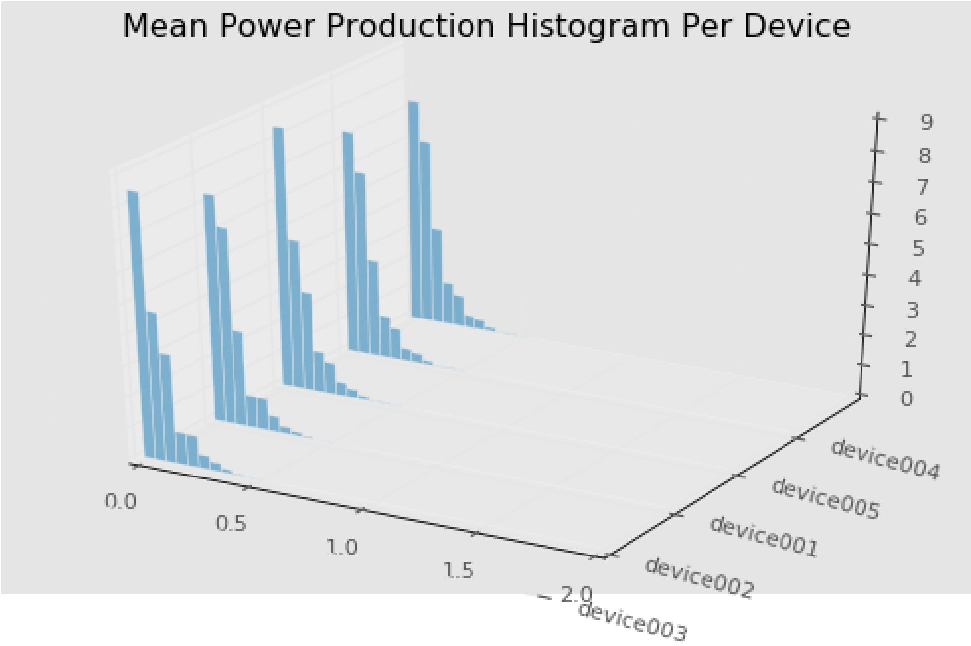

Figure 4-24 Mean power histogram per device

Single Device Power Matrix (Mean Over All Directions) [kW]

m0 [m] \ Te [s]	0.50	1.50	2.50	3.50	4.50	5.50	6.50	7.50	8.50	9.50	10.50	11.50	12.50	13.50	14.50	15.50	16.50	17.50
0.25	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0
0.75	0	0	0	0	3	7	9	8	8	11	11	9	8	5	4	3	2	2
1.25	0	0	0	0	9	17	26	23	23	31	29	25	21	16	13	11	8	7
1.75	0	0	0	0	19	35	50	45	45	61	56	48	40	32	26	21	17	14
2.25	0	0	0	0	31	58	82	75	75	100	90	78	65	53	43	35	29	24
2.75	0	0	0	0	47	87	121	113	112	148	133	114	96	78	64	52	43	35
3.25	0	0	0	0	62	122	169	158	156	202	182	157	131	108	88	72	59	49
3.75	0	0	0	0	87	162	223	210	208	265	238	205	172	141	116	95	78	65
4.25	0	0	0	0	110	207	285	270	267	334	301	259	217	180	147	121	99	82
4.75	0	0	0	0	137	260	355	338	334	412	371	318	268	222	182	149	123	102
5.25	0	0	0	0	168	314	429	413	408	496	446	385	323	268	219	180	149	123
5.75	0	0	0	0	200	376	512	495	490	588	525	455	382	317	260	214	177	147
6.25	0	0	0	0	236	432	601	585	579	685	616	530	446	370	305	251	207	172
6.75	0	0	0	0	276	514	697	683	675	788	708	612	514	427	352	290	239	199
7.25	0	0	0	0	317	591	799	788	779	900	808	697	586	487	402	331	274	227
7.75	0	0	0	0	362	672	907	901	890	1014	912	787	663	551	455	375	310	258
8.25	0	0	0	0	405	758	1021	1021	1009	1139	1022	883	744	618	511	422	349	290

Figure 4-25 Single device power matrix

The simulation also gives a 10-year projection of the power developed. The results show that the plant is expected to generate consistent energy of 3.7GWHr per annum over the period before the system starts to fail.

4.9 Discussion of results

The results obtained using Simulink®, are in close agreement with the theoretically-calculated results. It's likely this is because the Simulink® models are directly developed from the mathematical models. However, they show the expected changes in output as the input changes.

The results from the DTOcean® simulations show that the power developed in the system is about 20 percent of the estimated power. This is because the internal models of the devices are not deduced from the mathematical models. Also, the basic simulation strategy was used. The results show that there is a need for an iterative approach to the design so that optimum conditions are deduced and used.

4.10 Conclusion

The tidal barrage power plant has been simulated as a whole, using both Simulink® and DTOcean®. The results show a small difference. Calculations in Chapter Three estimate a capacity of 16GWhr, while Simulink® estimates 16.06GWhr. DTOcean® gives a lower estimate of 3.7 GWhr per annum. A close link can be established if the WEC device is simulated using Matlab®, and the results used as inputs to the model in DTOcean®. The two-simulation software can be used together for an optimised tidal barrage system design.

CHAPTER FIVE

ECONOMICS AND COSTING OF TIDAL POWER PLANT

5.1 Introduction

The tidal power plant under consideration was designed and simulated, and the results are summarized below. The plant was designed to use a tidal barrage and with a generating capacity of 10MW achieved through the use of 5 X 2 MW turbines. This chapter will show the calculation of the levelised cost of energy (LCOE) for the plant, the turbines available in the market, and their cost, existing tidal power plants in the world, including the initial capital required and the operation and maintenance cost. The findings are verified using HOMER software.

5.2 Calculation of cost of energy

The cost of energy is quantified using the levelised cost of energy (LCOE), which is a constant unit cost of a payment stream that has the same present value as the total cost of building and operating a power plant over its life [60, 61]. It is used to evaluate the feasibility and competitiveness of an electricity-generating system. In its simplest form, the lifetime cost can be measured when divided by energy production. It is critical in making informed decisions to proceed with the development of a power generating plant. It is the price of generation per kilowatt-hour or megawatt-hour. Its significance is also in determining the cost of energy at which if the electricity is sold, it will enable the investment to break even before the plant life expires.

The diagram below shows the LCOE concept in simple terms.

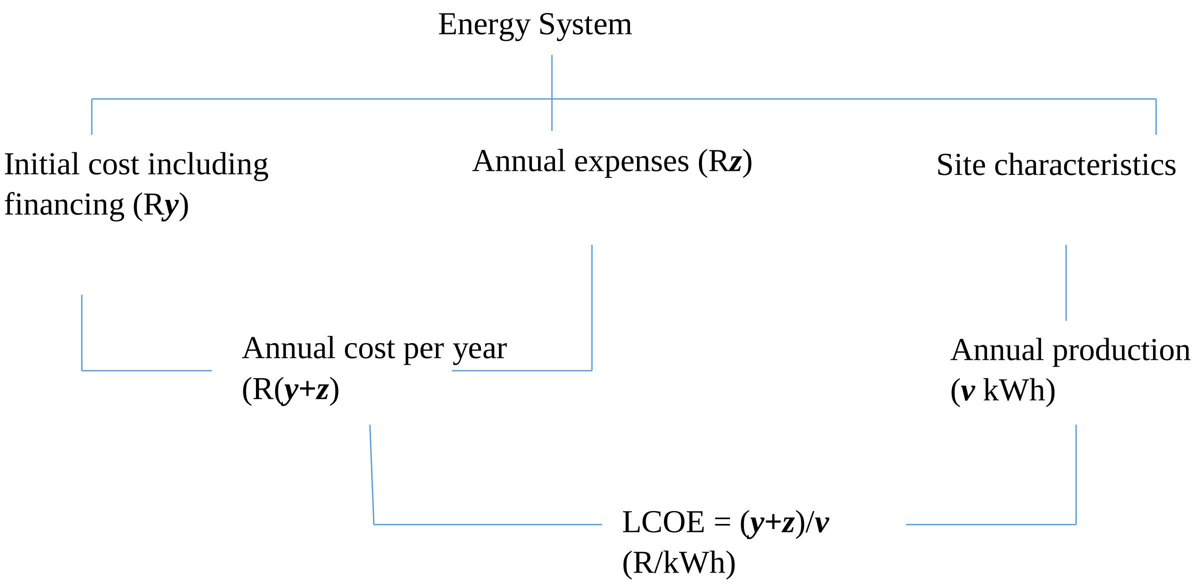

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Figure 5-1 The LCOE concept [62]

LCOE has basically three components, which are:

Initial capital expenditure (CAPEX),

Annual expenses of operation and maintenance (OPEX), and

Annual energy production (AEP).

More refined calculations will include:

Estimated useful system life, in years

Taxes

Discount rate

Operation and maintenance costs, usually estimated to be 2.5% of the total installed cost,

Investment capital, and

CO_2 emission charges and performance

CAPEX includes construction cost, electrical system infrastructure, and installations as well as predevelopment costs. OPEX includes operation and maintenance costs, insurance costs, decommissioning costs, and any other associated costs.

Equation (1) is used to model the LCOE,

$$LCOE = w + f + c \times \Delta \tag{5-1}$$

Where, w is the time-averaged variable cost per kWh, f is the levelised fixed operating cost per kWh, c is the levelised capacity cost of facility per kWh, and Δ is the tax factor covering the impact of income taxes, depreciation tax shield, and investment tax credit.

$$c = \frac{SP}{m \times CF \times \sum_{i=1}^{T} x^{i-1} \times \gamma^{i}} \tag{5-2}$$

Where, SP is the system price, acquisition cost of generating capacity (R/kW), m is the number of hours per year, equal to 8 760 hours, CF is the capacity factor of generating capacity,

T is the useful lifetime of the generating facility, in years, x^{i-1} is the system degradation factor in year i, γ^{i} is the discount factor based on the cost of capital, r

$$\gamma = \frac{1}{1+r} \tag{5-3}$$

$$f = \frac{\sum_{i=1}^{T} F_i \times \gamma^{i}}{m \times CF \times \sum_{i=1}^{T} x^{i-1} \times \gamma^{i}} \tag{5-4}$$

Where, F_i is the fixed operating cost in the year i of generating facility (R/kWh)

$$w = \frac{\sum_{i=1}^{T} W_i \times x^{i-1} \times \gamma^{i}}{\sum_{i=1}^{T} x^{i-1} \times \gamma^{i}} \tag{5-5}$$

Where, W_i is the variable operating cost in the year i of generating capacity (R/kW).

The tax factor is given by;

$$\Delta = \frac{1 - ITC - \alpha(1 - ITC \times \delta) \times \sum_{i=1}^{T} d_i \times \gamma^{i}}{1 - \alpha} \tag{5-6}$$

Where, ITC is the investment tax credit (%), α is the effective corporate income tax rate (%), d_i is the allowable tax depreciation rate in the year i (%), δ is the capitalization discount for depreciation purposes.

If the above information is available, then HOMER can be used to calculate the LCOE. Other LCOE calculators have been developed for the same purposes and can be found online. However, they basically follow the theoretical analysis presented above with a few alterations according to financial policies in the country of implementation.

5.3 Available turbines and generators in the market.

Table 5-1 Available turbines and generators in the market [4, 62]

Turbine Supplier	Turbine Type	Efficiency (%)	Output power (MW)	Output Voltage (V)	Cost ($)
Chengdu Forster Technology, China	Kaplan	89	0.3-3		160 000
Chong Qung Enrich Engineering (madeinchina.com)	Horizontal Francis hydro-generator (10m head min)	87	1, 2 and 3	Up to 35kV	90 000
	4m head min	85	0.3		35 000

5.4 Existing (E) tidal power plants

Table 5-2 Existing tidal power plants [4, 61, 62]

Location	Year	Installed Capacity (MW)	Turbines used	Cost (million)	AEP (GWh)	$/kW production cost	LCOE (R/kWh)
Sihwa Lake, South Korea (E)	2015	254	10X25.4MW bulb turbines (90% efficient)	US$298	552.7	117	0.33 R/kWh
La Rance, France (E)	1966	240	24X10MW reversible bulb turbines (90% efficient)	US$817	540	382	0.67 R/kWh
Swansea Bay, UK (E)	2019	240	Reversible bulb turbine	£850	400		N/A

5.5 Costing of power plant

The tidal plant design specifications are:

190m long dam wall, 25m width, 10m height

Basin area, A = 706 560m^2

Five - 2MW turbines, 0.5m/s cut-in speed, 2.25m/s rated speed, 5.5m/s cut out speed

Three-phase generator output at 3.3kV

Discharge rate = 73.6m^3/s

Water head = 6m

30m channel width

Annual production = 3.7GWh

At the time of writing, no document was found to give details of the South African national policy on tidal energy projects. This has led to the use of information from other established projects in the world, and they are cited accordingly.

The cost of damming is assumed to be US$ 393/ml, which converted to R 6 547.38/ml of the reservoir, where 1ml equals 1 000m^3 [63, 65]. Operation and maintenance range between 0.14% to 0.35% of capital investment on plant components [63].The discount rates for Tidal power are not available, but values available are 14.75% for solar and 15.75% for wind [64].

The cost components of the power plant are presented in the table below to represent the capital investment:

Table 5-3 Capital investment costs for developing the power plant

Component	Rating	Unit	Rand (R)
Reservoir Capacity	7 065 600	m^3	R 46 650 000
Turbine Hall concrete	750	m^3	R 13 330 000
Turbine and generator	5 X 2	MW	R 19 990 000
Turbine plant equipment			R 350 000
Electrical connections			R 10 410 000
Sluice gates and accessories	5		R 23 320 000
Access jetty	5		R 1 730 000
Navigation lights	25		R 350 000
Auxiliary components	1%	Installation cost	R 2 800 000
Labour	15%	Installation cost	R 7 000 000
Total Cost			R 125 930 000

The cost of operation and maintenance is taken to be 2.5% of serviced components cost.

Cost of serviced components includes the cost of:

Turbine and generator

Electrical connections

Navigation lights

Auxiliary components

25% of turbine plant equipment

The total cost of serviced equipment is R 33 636 540

$$O\&M = 0.025 \times R\ 33\ 636\ 540 = R\ 8\ 409\ 13.50 \qquad (5\text{-}7)$$

The cost of construction and operation per kW is therefore:

$$SP = \frac{R\ 125\ 930\ 000}{10\ 000kW} = \ 12\ 593\ \ R/kW \tag{5-8}$$

Cost of operation and maintenance is taken to be 2.5% of installation cost and the discount rate taken at 15%. The cost of operation per kilowatt-hour is given by;

$$F_i = \frac{R\ 125\ 930\ 000}{37\ 000\ 000} = \ 34.04\ R/kWh \tag{5-9}$$

Using equation 2,

$$\mathrm{c} = \frac{\mathrm{R\ 12\ 593}}{8760 \times 0.2 \times 40 \times 0.87 \times 0.05} = \mathrm{R\ 4.13}$$

Using equation 4,

$$\mathrm{f} = \frac{\mathrm{R\ 34.04} \times 0.87}{8760 \times 0.2 \times 40 \times 0.87 \times 0.05} = \mathrm{R\ 0.0097}$$

$$\mathrm{w} \approx \mathrm{f} = \mathrm{R}\ \ 0.0097$$

Assume tax at 15% due to lack of sufficient data:

$$\therefore \mathrm{LCOE} = \mathrm{R}(0{,}0097 + 0.0097 + 0.15 \times 4.13) = \ 0.64\ \mathrm{R/kWh}$$

The calculated cost for Tidal energy is 0.64 R/kWh and the cost for solar is 0.75 R/kWh. It can be seen that tidal energy is a viable option [66].

5.6 Using Homer Simulations

The simulation of the system using HOMER also assists in getting the cost of production of energy and also maintenance. HOMER simulates possible combinations of the components that make up the system. The ranking is given in terms of the net present cost (NPC), which is a statistic representing the total costs that the system incurs in its lifetime, less the revenue it earns over its lifetime.

Table 5-4 The basic input parameters using HOMER

Component	Value	Units
Discount rate	15	%
Inflation rate	2.43	% per annum
Capacity Shortage	10	% per annum
Project life	40	years
Hydro generator	10	MW
Capital cost	125 930 000.00	R
Replacement cost	47 230 000.00	R
O&M per year	8 409 13.50	R

5.7 Payback Period

According to eThekwini Municipality, electricity is charged at R1, 82 per kWh [67].

Cost to produce = 1 000 x 1.82 = R 1 820 (5-10)

Cost per month (30 days) = R 1 820x 30 = R 54 600 (5-11)

Cost per year (12 months) = R 54 600x 12 = R655 200 (5-12)

Assume an average increase of 15% per year,

2nd year = (100+15) x 655 200 = R 753 480

Table 5-5 The payback period for the power utility

Year (Y)	%	Cost (R)
1	(100+15) = 115	R 655 200
2	(100+15) = 115	R 753 480
3	(100+15) = 115	R 866 502
4	(100+15) = 115	R 996 477.30
5	(100+15) = 115	R 1 145 948.90
6	(100+15) = 115	R1 317 841.23
7	(100+15) = 115	R 1 515 517.41
8	(100+15) = 115	R 1 742 845.03
9	(100+15) = 115	R 2 004 271.78
10	(100+15) = 115	R 2 304 912.55
11	(100+15) = 115	R 2 650 649.43
12	(100+15) = 115	R 3 048 246.84
13	(100+15) = 115	R 3 505 483.87
14	(100+15) = 115	R 4 031 306.45
15	(100+15) = 115	R 4 636 002.42
16	(100+15) = 115	R 5 331 402.78
17	(100+15) = 115	R 6 131 113.20
18	(100+15) = 115	R 7 050 780.18
19	(100+15) = 115	R 8 108 397.20
20	(100+15) = 115	R 9 324 656.78
21	(100+15) = 115	R 10 723 355.30
22	(100+15) = 115	R 12 331 858.59
23	(100+15) = 115	R 14 181 637.38
24	(100+15) = 115	R 16 308 882. 99
Total		R 120 539 524.61

After considering the capital cost of the system and calculating the payback period of thee power utility it can be assumed that it will take approximately 23 years for the payback period.

The HOMER software gives the following results for the plant assuming a community load of maximum 10MW

Table 5-6 HOMER software results

Quantity	Value	Units
Annualised capital	5 606 454.92	R
Annualised O&M	1 681 827.00	R
Annual production	21 613 143.00	kWh/yr
Levelised cost (generator)	0.29	R/kWh
LCOE (system)	0,28	R/kWh

The LCOE for the generator is 0.29 R/kWh and is almost half of the calculated value. This is because some components like the damming and channels are not explicitly defined in HOMER. The value is, therefore based on the performance of the generator.

The overall system LCOE is R 0,28 because there is no input on the income generated from the plant. In reality, if the generated income can be predicted and incorporated, the value is expected to be far much lower.

5.8 Conclusion

The tidal power plant development of economics and costing has been presented. HOMER software has been used to determine the costing of the system. The currency has been converted to suit the currency in South Africa. At the time of conversion, the United States dollar traded at $1 = R16.66. The LCOE cost shows to be approximately 0.64 R/kWh, which translates that the LCOE is comparable to that of existing tidal power plants.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The results of Chapter Three and Chapter Four show that the development of a tidal wave barrage system for South Africa is feasible and can increase the power generation for South Africa. However, there are noticeable differences in values derived from the results, and these need to be clarified. The tidal barrage basin area was derived using the plant-rated power of 10MW. This calculation assumes the generating unit is at 100percent efficiency; however, the actual efficiency is a function of many other variables that are equipment- and site-specific. This system only operates for 4 hours daily. Resultantly, the value of the calculated area may have a bearing on the results determined from DTOcean®. The turbine and generator choices were determined by the tidal wave properties of the selected site. It can be observed that the available head has a significant bearing on these choices. These may be changed if the actual head available at a site it measured in a specific experiment with such a focus. This change will affect both the Simulink® and DTOcean® simulation results. Theoretical calculations showed that the designed system could generate up to 12MW of power against a designed capacity of 10MW. The Simulink® results showed that the generation is approximately equal to the designed capacity, while the DTOcean® simulations showed that the generation is 20 percent of the designed capacity. The theoretical and Simulink® results show overlap, but there is a considerable difference between the DTOcean® simulation results. The design and development of a tidal wave barrage system for South Africa have been presented. The design was guided by the existing theory about tidal waves and tidal energy systems, and this theory was presented. The theory was used in developing a design and model for the tidal barrage system, and the calculations were made using the underlying theory. The data for Durban was used as input in the model, and the generating potential for Durban was evaluated using the available data. The South African coast line has the potential to generate tidal energy. This plant can be implemented along coast lines in areas to enable the availability of electricity in remote/rural areas in South Africa. This plant has the ability to run independently without affecting the current National electrical grid in South Africa.

6.2 Recommendations

Based on the conclusion of the results of this research the following recommendations are made:

- The design of the tidal barrage system has been modelled and it shows that this system has the potential to produce clean electrical energy. As new data becomes available it should be used to model this system so a comparison could be made.
- Different types of generators and turbines could be used to determine if significant changes with the output power be noticeable.
- The DTOcean® simulation considers more than just the tidal wave current and the head. It takes into account the hydrodynamics and shear properties of the site. Resultantly, it shows that most of the present values in the DTOcean® simulation need to be changed for a specific site. However, not all the data was available for underwater properties. The results may be improved by improving the model, and including the physical site properties, which neither the Simulink® nor the theoretical calculations take into consideration.
- The theoretical design and model, combined with the Simulink® and ® simulations, showed that it is feasible to generate power from a tidal wave barrage system in Durban. The results also suggest that there is a need for focused efforts in acquiring data specifically for designing tidal energy power plants. The economics and costing of the energy of the tidal plant have been calculated. The overall potential can be approximated to 10GWHr per annum, and this amount can go a long way in adding to the already existing generation, while also lowering the carbon emissions from South African power plants.

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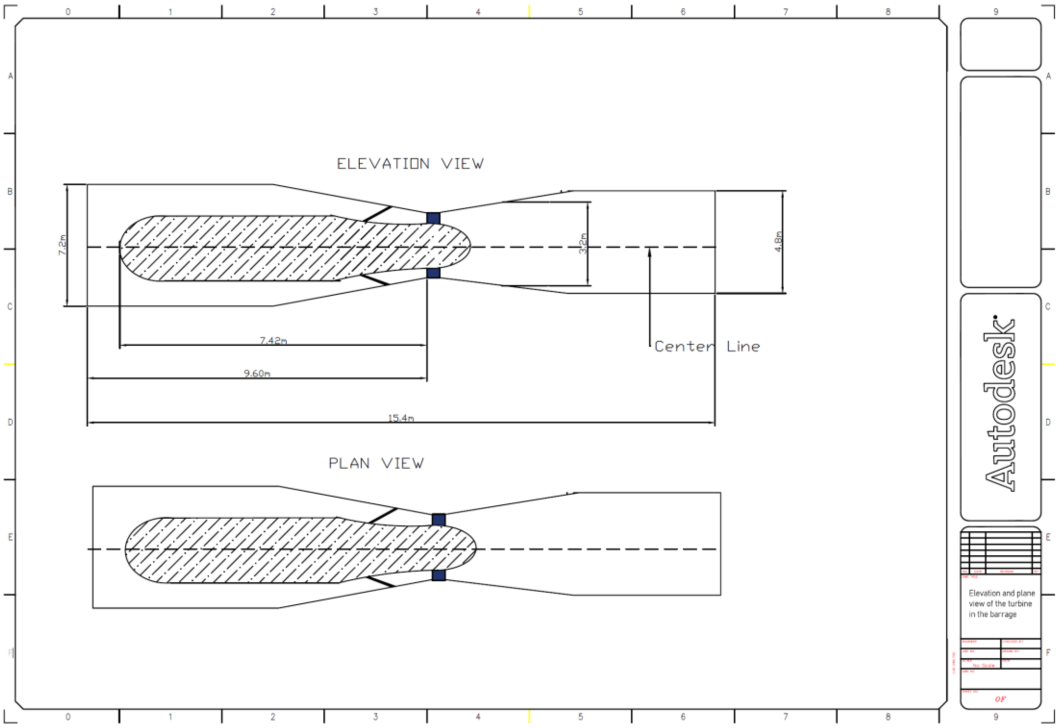
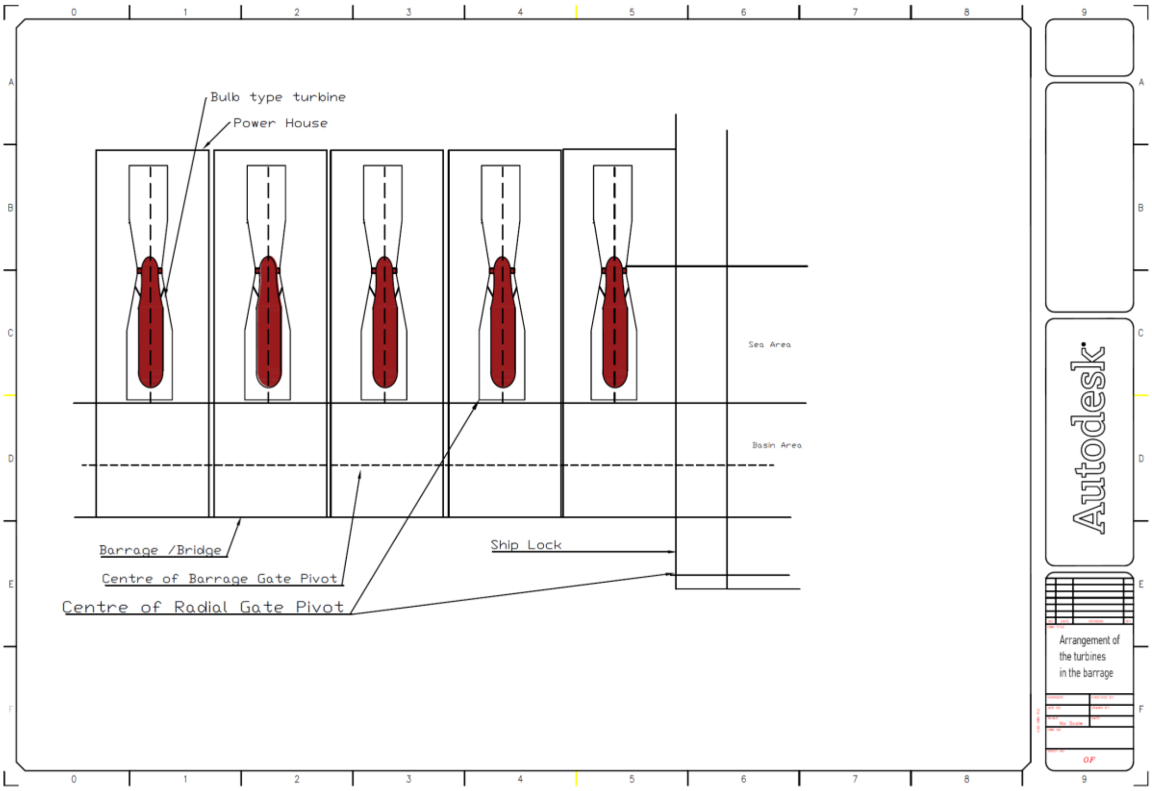
Appendix A



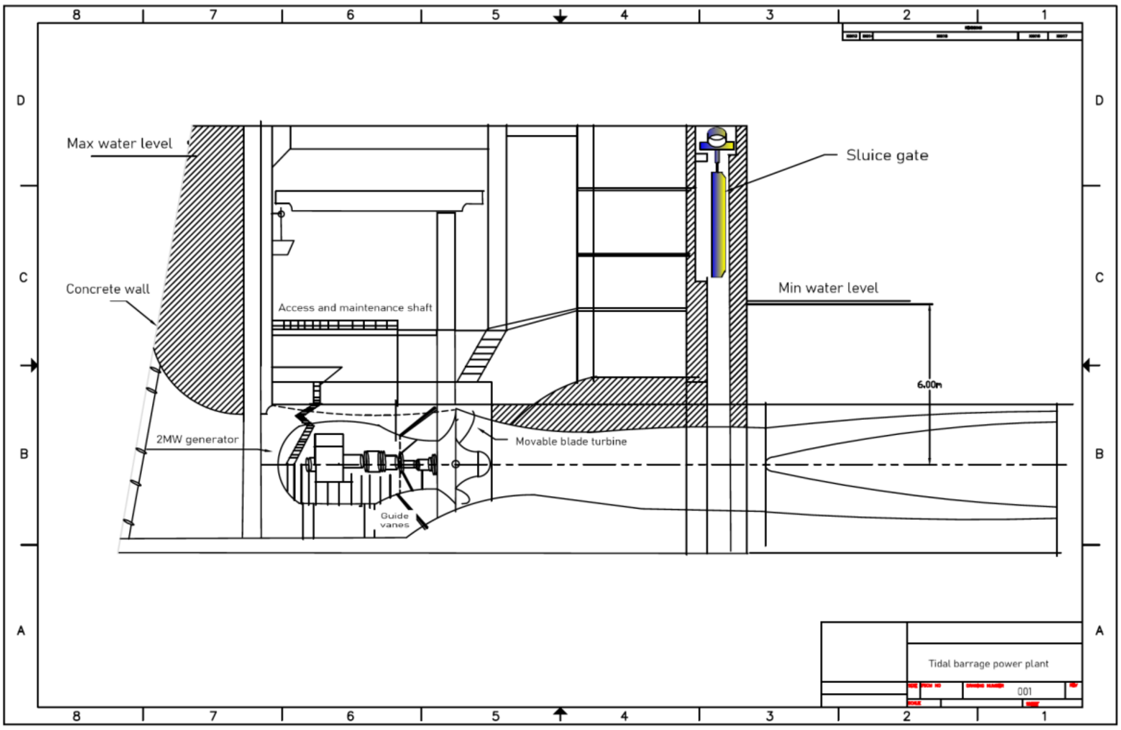
Appendix A- Elevation and plane view of the turbine in the barrage

Appendix B



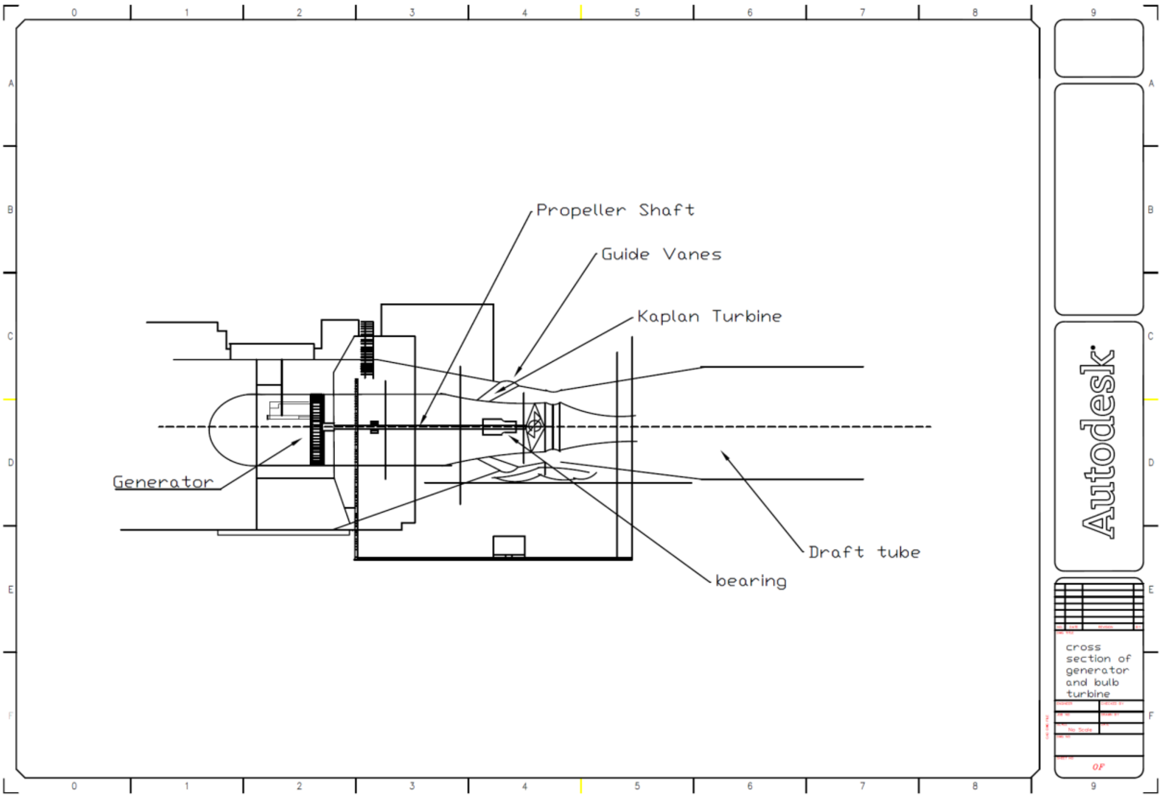
Appendix B- Arrangement of turbines in the barrage

Appendix C



Appendix C- Tidal barrage generator channel showing the positioning of generating units and power-connecting corridor

Appendix D



Appendix D- Cross-section of generator and bulb turbine