A Simulation Model for Tidal Energy Extraction in Nigeria Using Tidal Current Turbine

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***Abstract* - The study deals with the development of a Matlab-Simulink model to simulate a Tidal Current Turbine. The purpose of the simulation model is to evaluate the potential for Tidal Current Power Generation in Nigeria. A case study of Qua Iboe River is presented. The river is tidally dominated, and experiences a tidal range of about 2 meters during spring tide periods. The tides in the site were analyzed using a MATLAB program known as World Tides. Analysis from the World Tides gave the corresponding value of the amplitude, frequency and phase for each tidal constituent. A modelling of the tidal current velocity profile was performed and the results from the model shows that Qua Iboe River has an average current velocity of about 0.82 m/s. Power from a typical single turbine was modeled in MATLAB/Simulink, and the resulting power was 37.84 KW. *Cost/KWh was estimated to be 104.4 naira.* In conclusion, Qua Iboe River which flows in a North-South direction to the Atlantic Ocean has the potential to be a location for Tidal current turbine installation. This may not be financially feasible under current technology. However, with the great interest shown in this area in recent times, lower installation cost, and the urge to "go green", this will be applicable in the future.**

Keywords – Sustainable Energy, Tidal Currents, Tidal Energy Conversion System, Modelling, OpenHydro Turbine

I. Introduction

In the last ten years, energy research has been focusing on power generation from alternative energy sources. One of the latest developments in alternative energy sources is the use of tidal power to generate electricity. Tidal power, also known as tidal energy can be described as the energy released by the interaction of the gravitational forces between the oceans and the astronomical bodies [1]. The uniqueness of tidal power is that it can be accurately forecasted over long time horizons [2]. This means that it would be easier to integrate tidal power into the national grid compared to other alternative energy sources.

The extraction of energy from coastal tides can be achieved in two ways [3]. The first involves the building of a barrage across an estuary to exploit the rise and fall of the tide, while the second, which is the main focus of this study, involves the use of tidal current turbines to generate electricity from the horizontal movement of the water.

The extraction of energy from a tidal flow involves the conversion of kinetic energy in a water current into a mechanical energy which can then be used to drive a generator. The main components of the system are the tidal flow, tidal turbine, drive train, and the generator. In search of sites for tidal turbine installation, sites with water flow speed greater than 2m/s are generally considered to achieve a significant amount of tidal power [4]. However, because of a limited number of sites with high-speed currents and growing demand for green energy, tidal energy in low-speed currents is also gaining an increasing attention. For example, in a tidal energy survey reported in [5], an efficient permanent magnet generator was utilized to harvest tidal power from slowly moving currents, around 1m/s.

There are so many potential sites for tidal current turbine installation all over the world. These sites include the English Channel, the Bay of Fundy, the Arctic Ocean, the Amazon, and the Gulf of Mexico [6]. Several recent studies have been conducted in Europe, Asia, and America to estimate the exploitable tidal stream resources in these regions. In the United Kingdom (UK) for example, [7] estimated a 2.5 GW resource, representing around 6% of UK electricity demand in 2004. In the United States, a wave and tidal power assessment was conducted in the coastal region of South Carolina, North Carolina, North Florida, and Georgia [8]. The Bay of Fundy has one of the largest tidal ranges in the world. Several assessment studies have been conducted for this region. The study in [9] considered the tidal power available in the minas passage in the Bay of Fundy for electricity generation using in-stream turbines.

In spite of the many locations with significant tidal current energy globally, the technology is not yet economically viable [10]. Some of the issues affecting the development of tidal energy technology include: Installation and loading challenges, maintenance, electricity transmission, and environmental impact [10]. Therefore if tidal energy extraction is to be implemented on a large scale, much more research and development is necessary.

The Nigerian coastline lies along the Gulf of Guinea with several locations of tidal predictions and four primary tidal stations [11]. These locations include, Akassa, Lagos Bar, Bonny, Calabar, Qua Iboe etc. It is then, important and beneficial to quantify the electrical power potential harnessed by a tidal current turbine from these locations. This paper therefore presents a development of a Matlab–Simulink simulation tool, to assess the extractable electrical power through the modeling of the water current and the tidal turbine rotor.

The proposed model has been used to assess the extractable power from the Qua Iboe River, since it is a possible site for tidal current turbine installation. The block diagram of the study is shown in figure 1.

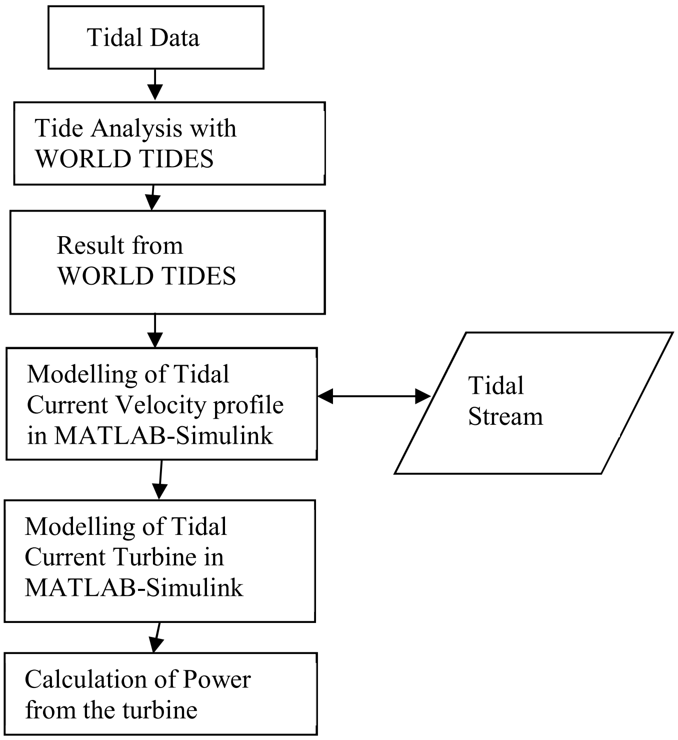

Figure 1: Block Diagram of the Proposed Design

II. STUDY AREA

The study area is a North-South trending estuary originating from Umuahia Hills in the south East Nigeria and opens directly into the Atlantic Ocean as shown in Figure 2. The depth of the river is varied from around 5 meter in the area near to the coastline to the deepest part in the middle around 40 m [12]. The Qua-Iboe estuary is an appropriate location for the placement of a tidal turbine and has been chosen because it has one of the highest tidal current speeds in Nigeria coupled with adequate depths suitable for tidal turbine installation [13].

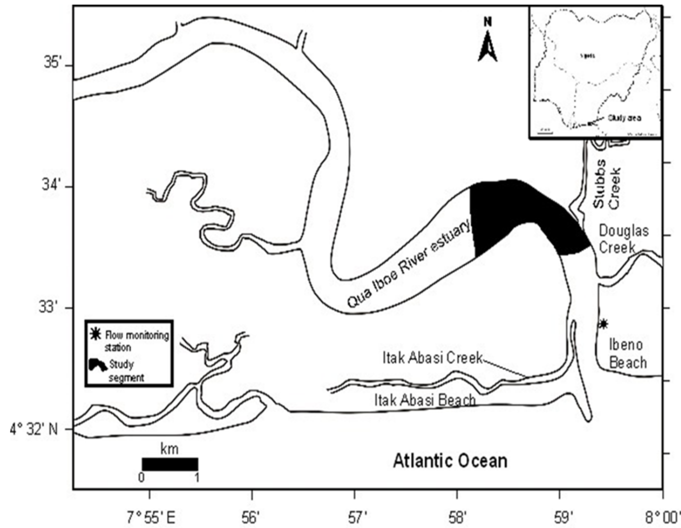

Figure 2 Geographical map of study area [14]

III. MODELLING OF THE WATER CURRENT

A Tide Analysis

In this work, a Matlab program known as World Tides was used for the analysis of the tides. World Tides uses the harmonic model for the analysis and prediction of tides. This Model assumes that tidal elevation is represented by the summation of harmonic components, each component being represented by an oscillation at a known frequency of astronomical origin. The equation for the water level elevation is given as:

$$h(t) = h_0 + \sum_{j=1}^{m} f_j H_j \cos\left(w_j t + u_j - k_j\right) \qquad (1)$$

Where $h(t)$ is the predicted water level depth, f_j is the lunar node factor, H_j is the mean amplitude, h_o is the mean water level, w_j, u_j, k_j represent the frequency, nodal phase and phase angle respectively for the jth tidal constituents, and m is the number of constituents.

Using the above equation, World Tides decomposes the tide into five (5) predominant tidal constituents (M2, O1, N2, S2, K1) found in the location. The corresponding values of the tidal amplitude, tidal phase, and angular speed for each tidal constituent as obtained from the tide analysis can be seen in table 1.

Table 1 Tidal Constituents and their properties

Tidal Constituent	*Amplitude (m)*	*Phase (degrees)*	*Frequency (hr^{-1})*
M2	0.86	31.0	0.0805
S2	0.11	52.5	0.0833
N2	0.19	26.4	0.0790
K1	0.12	20.5	0.0418
O1	0.06	218.0	0.0387

The harmonic method is based on the conception that the tide is the summation of the partial tides (tidal constituents), and each partial tide has a unique amplitude and phase at any given location. By summing an abundant number of the partial tides, the user gets a wave form which is nearer to the observed tide at a particular location. Studies have shown that including more tidal constituents will provide more accuracy of the waveform generated.

Most of tidal constituents are relatively small and can be neglected for practical tide prediction. In this work, the five aforementioned tidal constituents above where used in the tide analysis and prediction, while the other tidal constituents where considered quite small and thus neglected.

B Modelling of Tidal Current Velocity Profile

The movements of the tidal streams are considered as sinusoids moving in and out of the tidal phase. The tidal currents can therefore be modeled as a stream of harmonics according to the following equation:

$$V(t) = \sum A_i . \sin(2\pi f_i t + \theta_i) \qquad (2)$$

Where $V(t)$ is the tidal current speed with respect to time, A_i is the amplitude for the ith harmonic constituent, f_i is the frequency for the ith harmonic constituent, and θ_i is the phase angle for the ith harmonic constituents.

Equation 2 above has been implemented in Simulink using function blocks for the five major tidal constituents (K1, M2, N2, S2, and O1) used in this work. These constituents have been added to obtain the resultant tidal current velocity profile. Figure 3 shows the Tidal Current Velocity profile as modeled in Simulink.

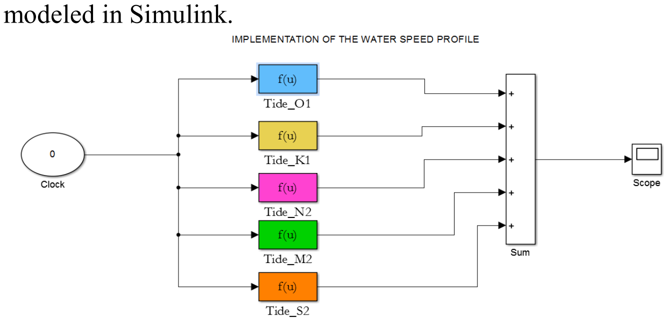

Figure 3 Model of the Tidal current velocity profile

IV. MODELLING OF THE ROTOR

The turbine model is of immense importance since it determines the amount of power harnessed from a water flow. Similar to other power plants or turbine, the power to be generated is dependent on the plant/turbine design [5]. In tidal energy conversion system, the available power is dependent on the speed of the tidal current and the diameter of the rotor. The amount of power available in a free flow of water is given by [2]:

$$P_{avl} = \frac{\delta . A_r . V^3}{2} \qquad (3)$$

Where δ is the seawater density constant = 1025

A_r = Rotor blade area

V = Tidal current velocity

Considering the efficiency of the plant design, the actual power from the turbine can be quantified as:

$$P_{act} = C_p(\curlywedge, \theta) * \frac{\delta . A_r . V^3}{2} \qquad (4)$$

Where C_p is the power coefficient, $\curlywedge$ is the tip speed ratio and θ is the turbine blade pitch angle.

The tidal current turbine has been implemented in Matlab-Simulink. The model has been designed by observing the transient simulations from other tidal energy location already in operation. By introducing saturation in its design, the power generated from the turbine is capped at a set limit for optimal operation. Figure 5 shows the model of the tidal current turbine as implemented in Simulink.

A Modelling of the Power Coefficient

The Power Coefficient C_p is not static but depends on the tip speed ratio ($\curlywedge$) and the turbine blade pitch angle (θ). This is given by:

$$C_p(\curlywedge, \theta) = c_1 \left(\frac{C_2}{\beta} - C_3 \beta \theta - C_4 \theta^x - C_5 \right) e^{-\frac{C_6}{\beta}} \qquad (5)$$

The parameters C_1 to C_6 and x are constants and particular to the turbine system type being considered. In this work, the OpenHydro turbine system has been selected and the parameter values are given below [15]:

c1 = 0.5, c2 = 116, c3 = 0.4, c4 = 0, c5 = 5, c6 = 21 [

Additionally, the parameter β is also defined as,

$$\frac{1}{\beta} = \frac{1}{\curlywedge + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \qquad (6)$$

Representing the tip speed ratio in terms of the linear velocity of the rotor blade and the tidal velocity, the tip speed ratio can be expressed as:

$$\curlywedge = \frac{linear\ velocity\ of\ rotor\ blade}{Tidal\ Velocity}$$

But

$$Linear\ Velocity = Radius\ of\ rotor\ blade * Angular\ velocity$$

Therefore, the Tip speed ratio can be written as:

$$\lambda = \frac{Rw_r}{V} \qquad (7)$$

Where w_r, the rotor angular speed and R is the rotor blade radius

In this study, the rotor radius for an OpenHydro turbine is R = 7.5m, and the cut-in speed is 0.7m/s [15]. The cut-in speed is considered as the initial speed at which the turbine starts to generate energy

The parameters λ, θ *and* β have been initialized in MATLAB and called to run the Simulink model. The subsystem of the power coefficient expressed in equation 5 has been modelled in Simulink as shown in figure 4. The parameter values c1 to c6 have been inputted as constants since they are considered static for the OpenHydro turbine type.

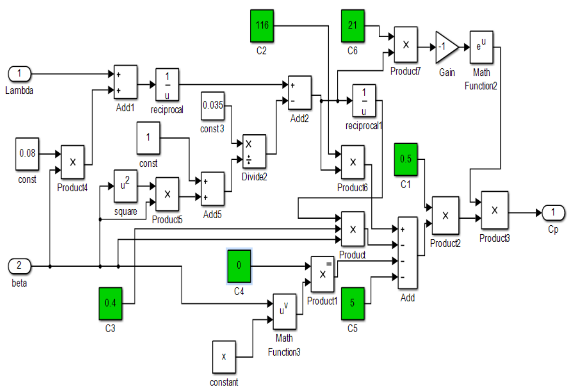

Figure 4 Simulink model of the power coefficient

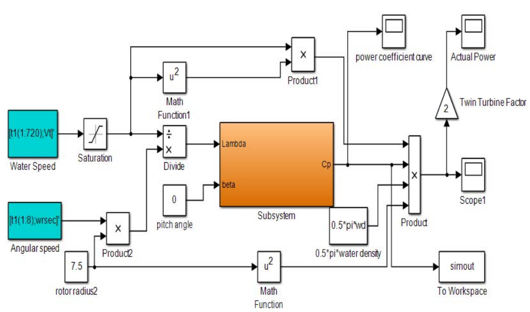

Figure 5 Simulink model of the Tidal Current Turbine

V. SIMULATION RESULTS

In this section, 30-day (720 hours) responses of the water speed and the actual power generated (expected) within this time frame have been analyzed.

A Simulation of the Tidal Current Velocity Profile

Figure 6 shows the simulation of the tidal current velocity profile for 30 days. The velocity amplitude is seen to be in the range of $\pm$1.15m/s. The simulation shows a high predictable rate of the tides and therefore, the energy expected at every given time can be obtained.

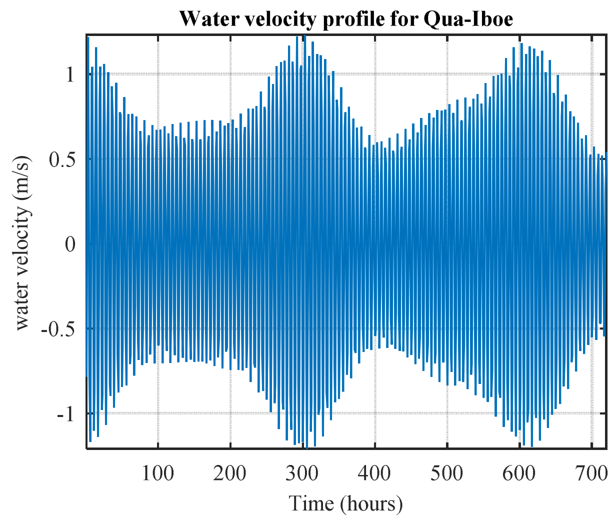

Figure 6 Simulation of Water Speed Profile for Qua-Iboe

B Simulation of the Power Coefficient relation with Tip Speed ratio (TSR).

Figure 7 shows a plot of the result of power coefficient against the tip speed ratio. The maximum value of the power coefficient, C_p is 0.41

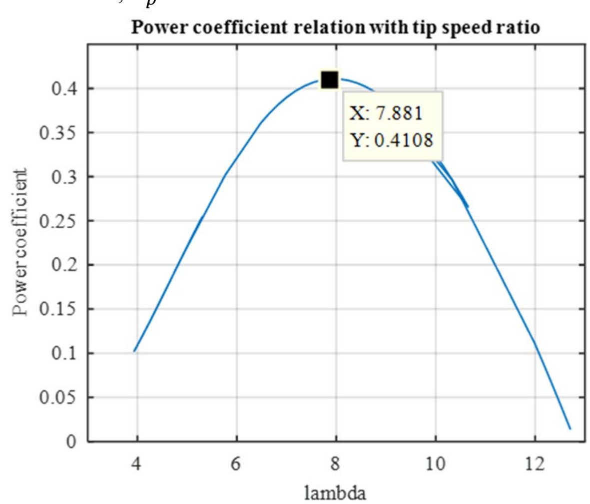

Figure 7 Power coefficient relation with tip speed ratio

C Simulation of the Tidal Current Turbine

Figure 8 shows the power curve of the turbine. The ratio of 72% has been assumed for a practically and economical operation of the tidal turbine. It has been shown in many literatures such as [16] and [17]; from the experiences of wind turbine and evaluating the optimal performance, the installed capacity of a turbine should be rated for a velocity equal to 0.75 (or lower) times the peak velocity at the site to be more economically viable [17]. In our work, this gives us a tidal turbine rotor design with 0.82 m/s.

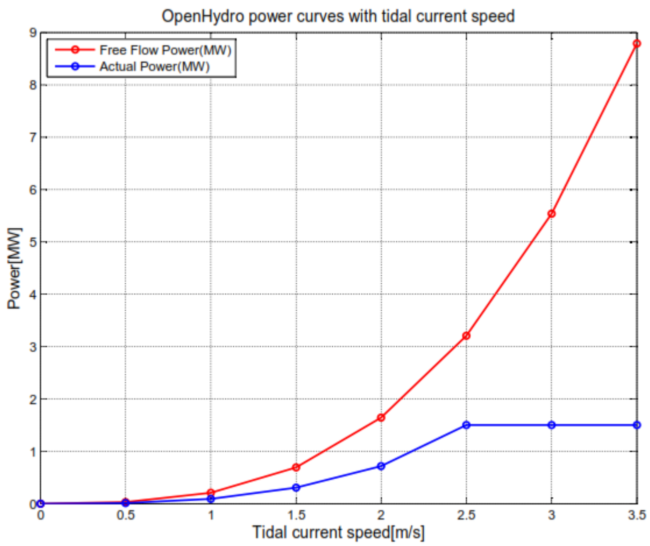

Figure 8 OpenHydro power curves with tidal current speed.

The resulting power of the 15m diameter twin rotor turbine is 37.84kw. This is approximately equal to that from equation (4) and according to turbine parameter, thereby verifying the validity of the generated Simulink model.

VI. ECONOMIC ASSESSMENT

In today's technology, in order to place tidal energy as an option for electricity generation and for it to be commercially acceptable, a more competitive price with power supply from hydro and other sources need to be considered. The study by [18] shows that there can be drivers aimed at influencing the consumer pricing, reducing the capital costs and allowing a higher profit margin. The assessment shown in table 2 gives an idea of what is required for deploying a twin-rotor turbine installation for electricity generation.

Table 2 summarizes the cost of electricity generation in Qua Iboe River using tidal current turbine.

Table 2 Cost of electricity using tidal current turbine

Capital and Operating costs (£m)	*0.059*
Installed Capacity (KW)	*37.84*
Cost/KW (£)	*1570*
Cost/KWh (£)	*0.18*

The operating costs and other running costs were drawn from the cost analysis for tidal deployment seen in [19]; this analysis included pre-deployment cost and other maintenance costs. However, for this analysis, the local trade and investment indices were considered.

From the information displayed in Table 2, Cost/KWh in naira (₦), at the exchange rate of five hundred and eighty naira to one British pound is:

$$\text{Cost/KWh (₦)} = 580 \times 0.18 = 104.4$$

VII. CONCLUSIONS

This paper shows the fundamental principle of power extraction from tidal currents. The tidal current turbine has been modelled using MATLAB/SIMULINK and well detailed analyses of the model setup have been described. Results obtained from the tide analysis shows that maximum flood and ebb velocities are in the range of 0.8-1.1 m/s and 0.8-1.15 m/s respectively. The extractable power for a particular turbine was 37.84kw. The physical characteristics of the site and its proximity near a transport facility (Mobil jetty) are favourable attributes for tidal energy extraction. Due to the relatively moderate velocities at this location, the generation of modest amount of energy is possible with the utilization of low-flow turbines. It is expected that, as technology matures, extraction of tidal power from sites with low speed current will become more viable.

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