Design selection of a tidal turbine for low velocity application

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Keywords: Tidal Turbine, Turbine Design, Turbine Blade, Design Matrix, Low Velocity

Abstract. Tidal energy is the sole renewable energy associated with tidal movements due to the gravitational and centrifugal forces between the Earth, the Moon, and the Sun. Although tidal energy is not yet widely used, it has the potential to generate energy for the future. It is a clean, renewable energy source and more predictable than other renewable sources of energy. Various existing tidal turbines have been developed in Europe, where tidal velocity is much higher than the tidal velocity in Brunei Darussalam, which is around 0.5 m/s. Therefore, this study investigates the design of a tidal turbine that can be effectively implemented in Brunei Darussalam. There are five conceptual designs, and each of them was evaluated with the evaluation matrix with a three-bladed commercial Horizontal Axis Tidal Turbine as the datum, obtaining the final design, which is Design 1, has the highest scoring point.

Introduction

Although tidal energy is not yet widely used, it has the potential to generate energy for the future [1]. It is a renewable energy source that produces energy from the ebb and flow of tides. Tides are caused by the combined action of gravitational forces exerted by the Moon and the Sun on Earth. As the Earth rotates, the position of a given area relative to the moon changes, creating the tides. Thus, a periodic succession of high and low tides. Two high tides and two low tides occur during the day. The high and low tide follows a sinusoidal curve. The difference between ebb tide and low tide is called the tidal range. When near a full moon or new moon, the range of tide is relatively high, known as spring tides, whereas nearly half-moon, the range of tide is relatively small, known as neap tides.

Several technologies can generate tidal energy, including tidal barrages, tidal lagoons, tidal fences, and tidal turbines. Both tidal barrages and tidal lagoons utilise the potential energy generated by the change in tidal height between high and low tides. It generates electricity via turning turbines similar to a hydropower. Tidal fences are turbines that operate like turnstiles, while tidal turbines are driven similarly to wind turbines but underwater. Both tidal fences and tidal turbines generate electricity by extracting the kinetic energy from the tidal currents. Ocean currents are 832 times denser than air and exert more force on the turbine, so ocean currents are able to generate more energy than winds at smaller size [2].

Khan et al [3] categorised the tidal technologies system into two classes: turbine and non-turbine. The turbine systems consist of axial (horizontal), vertical, crossflow, venturi, and gravitational vortex, whereas the non-turbine consists of flutter vane, piezoelectric, vortex-induced vibration, oscillating hydrofoil, and sail [3]. Recent technologies of tidal energy converters also include Archimedes Screw, Tidal Kite and Hydro-Spinna turbine. When the tide flows across the turbine, the turbine extracts the kinetic energy from the tides, reducing the kinetic energy of the tides and their velocity. Factors that affect tidal turbines are the orientation of the turbine, the number and blade profile used in the turbine, the twist and the tapper of the blade, and the rotor solidity of the turbine. According to Betz's limit, the theoretical maximum efficiency of a tidal or wind turbine is 59.3%. However, in practice, this limit cannot be reached, and the common efficiency is 35 to 45%.

Several methods have been developed to predict the performance of the turbine blade, one of them the Blade Element Momentum Theory (BEMT). Computational Fluid Dynamics (CFD) is another way to study different airfoils [4,5,6,7]. It can optimise the blades and perform turbine analysis [4,8]. Another method using a combination of Reynolds Average Navier-Stokes (RANS) equations and Shear-Stress Transportation (SST) type k – omega (ω) turbulence can perform with higher accuracy in investigating the performance of the turbine. Experimentations of the turbine blade in testing facilities to compare the CFD and the experimental data to validate the CFD model.

Designs of Turbine

Five conceptual designs were generated, based on existing tidal turbines that were known for low velocity applications. The first design is based on a Horizontal Axis Tidal Turbine with three-blades where the leading and trailing edge has a geometrical shape of one-third of cardioid. The rotation of the turbine is anticlockwise as the leading edge takes the lead. The shape of the hub is a semi-circle, and the blades are connected to a cylindrical shaft. This design is inspired by the Hydro-Spinna having the cardioid blades [1]. The illustration of the first design is in Fig. 1.

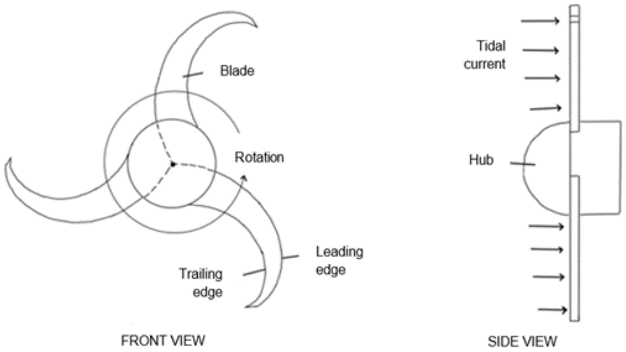

Fig. 1 First design.

The second design is also a Horizontal Axis Tidal Turbine design illustrated in Fig 2. This design is similar to the first design with a modification of extended blades in the axial direction. The turbine rotates in an anticlockwise direction.

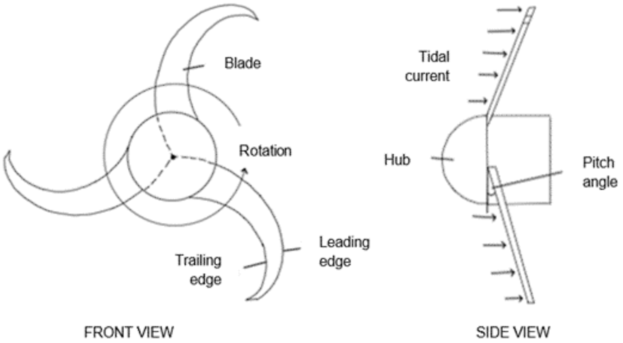

Fig. 2 Second design.

The third design is based on Vertical Axis Tidal Turbine with three blades shown in Fig. 3. Each blade's cross-sectional shape is one-third of cardioid, and the blades are mounted with a cylindrical shaft. The rotation of the turbine is anticlockwise. The Savonius Vertical Axis Tidal Turbine inspires this design, it provides uniform torque distribution along the whole rotation of the turbine.

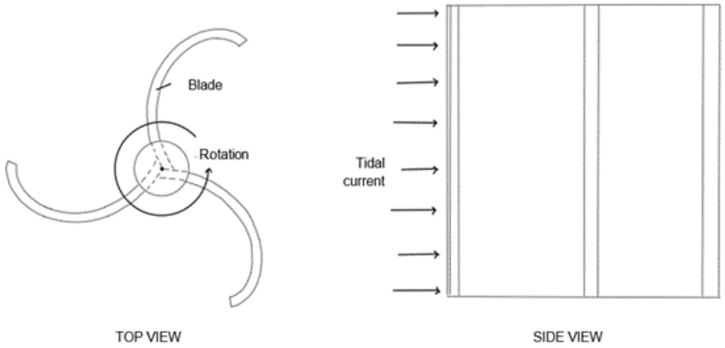

Fig. 3 Third design.

The fourth design is based on the Vertical Axis Tidal Turbine, and it is similar to the third design with twisted physical features presented in Fig. 4. This feature of the helical design had been proven to give better performance than the traditional Savonius Vertical Axis Tidal Turbine.

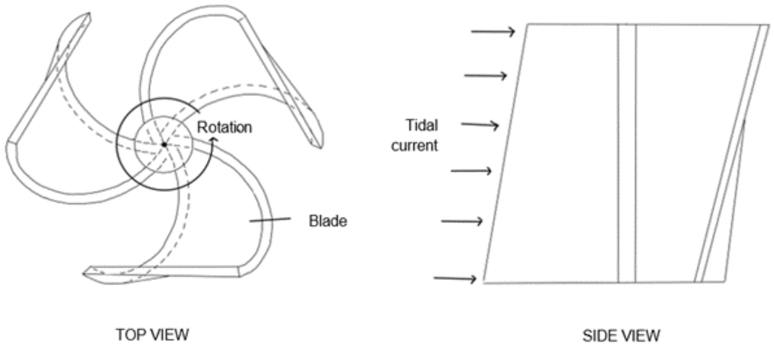

Fig. 4 Fourth design.

The fifth design is based on a Horizontal Axis Tidal Turbine with three blades which the leading and trailing edge are one-third of cardioid and circle respectively shown in Fig.5. The rotation of the turbine is anticlockwise. The hub is a semi-circle shaped and the blades are attached to a cylindrical shaft. This design was also motivated by the Hydro-Spinna turbine.

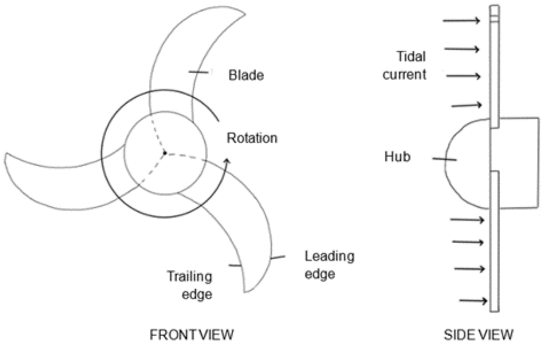

Fig. 5 Fifth design.

Design Selection of Turbine

The method of evaluation matrix is used to determine the final design by comparing all the preliminary designs with the datum. The criteria are the detailed requirements needed to be fulfilled, creating the successful product tabulated in Table 1 with the description. In finalising the design, each preliminary design was compared with the datum, a typical three-bladed commercial Horizontal Axis Tidal Axis, as illustrated in Fig. 6 by having the highest points due to its high efficiency and design popularity in real life deployment. The scoring system is based on the effectiveness of design according to properties. The design will gain a point if it is more effective than the datum and vice versa. The designs can also obtain no point with similar properties as the datum. This point system of the preliminary designs is tabulated in Table 2.

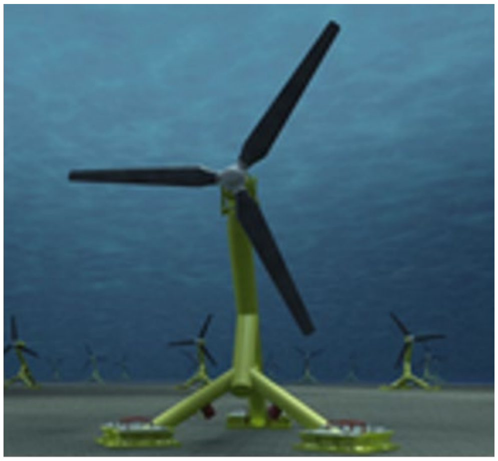

Fig. 6 Typical Horizontal Axis Tidal Turbine [9]

Table 1. Criteria of the design selection matrix

No.	Criteria	Description
1	Robust	● The turbine is able to sustain the tidal force. ● The turbine is able to withstand other marine conditions. ● The turbine is able to maintain its structural integrity.
2	Efficiency	● The power coefficient of the turbine is maximised.
3	Shelf life	● The turbine is able to last for more than 20 years with proper scheduled maintenance every six month.
4	Maintenance	● The blades are easy to maintain and repair.
5	Safety	● The blades should have no or less sharp edges.
6	Environment	● The turbine has little impact on the marine environment.
7	Fabrication	● The turbine should be easy to fabricate.
8	Transportation	● The turbine is easy to transport from one place to another.
9	Installation	● The turbine is easy to install. ● The turbine is easy to assemble and disassemble.
10	Performance	● The turbine is able to be performed in 0.5 m/s of water velocity.
11	Storage	● The turbine is easy to store.

Based on the calculated point from Table 2, the design having the highest points in the evaluation matrix is design 1. This design is more robust, safer, and easier to fabricate. In Fig. 7 illustrated the final design of the turbine in 3D model and its blade profile. The cross-sectional profile of the blade is that of the NACA 0018. The final design was verified using a previously validated numerical analysis in ANSYS Fluent. Fig. 8 shows the numerical domain that was used to investigate the power and thrust coefficient of the turbine using RANS and SST k-ω turbulence model. The solver used is Pressure-Based with absolute velocity formation in steady time. In calculating the C_P and C_T from the data obtained from the simulation uses the following mathematical expressions in Equations 1, and 2. The power and thrust coefficient performance will be plotted against the tip speed ratio (TSR) of the turbine. C_P is the ratio of the power generated by the turbine to the power available in the flow while C_T is the thrust ratio on the turbine to the axial load available in the flow.

$$C_P = \frac{Q\Omega}{0.5\,\rho A_s U^3} \tag{1}$$

$$C_T = \frac{T}{0.5\,\rho A_s U^2} \tag{2}$$

$$TSR = \frac{\Omega \times \mathrm{r}}{U} \tag{3}$$

where Q is the torque generated, Ω is the angular speed, ρ is the density, r is the radius of the turbine, A_S is the area of the turbine and U is the velocity of the water.

All simulations are performed at a tidal velocity of 3 m/s, resulting with a Reynolds Number (Re) of about 8.39×10^5 based on the diameter of the turbine. The calculated Re is over 2000, indicating that the flow is turbulent.

Table 2. Evaluation Matrix

Design	**1**	**2**	**3**	**4**	**5**	**6**
Robust	+	+	+	+	+	
Efficiency	+	=	-	-	+	D
Shelf life	=	=	=	=	=	
Maintenance	=	=	-	-	=	
Safety	+	+	-	-	+	A
Environment	=	=	=	=	=	
Fabrication	+	-	-	-	+	
Transportation	=	=	-	-	=	T
Installation	=	-	-	-	=	
Performance	=	=	=	=	=	
Storage	=	=	-	-	=	U

Total (+)	3	2	1	1	4	M
Total (-)	0	2	7	7	0	
Total (=)	7	7	3	3	8	
Total	+3	0	-6	-6	+4	

Note: + (+1 point): Property is better than datum. - (-1 point): Property is worse than datum.
= (0 point): Property is comparable to datum.

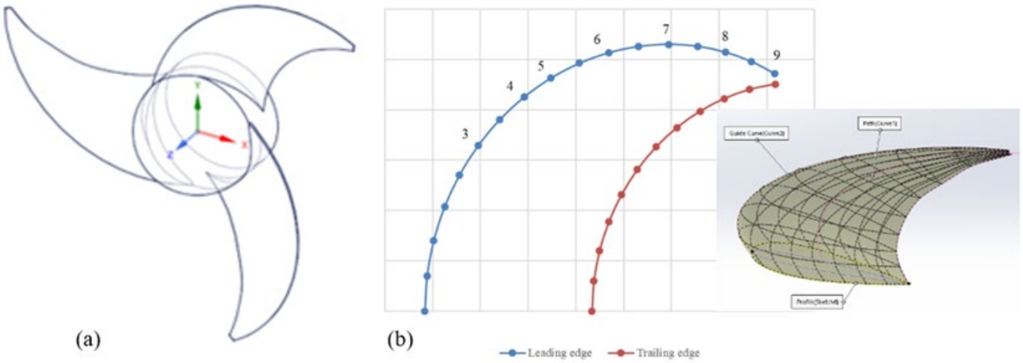

Fig. 7 (a) The 3D model of the finalised design turbine and (b) its blade profile with the NACA0018 cross sectional profile

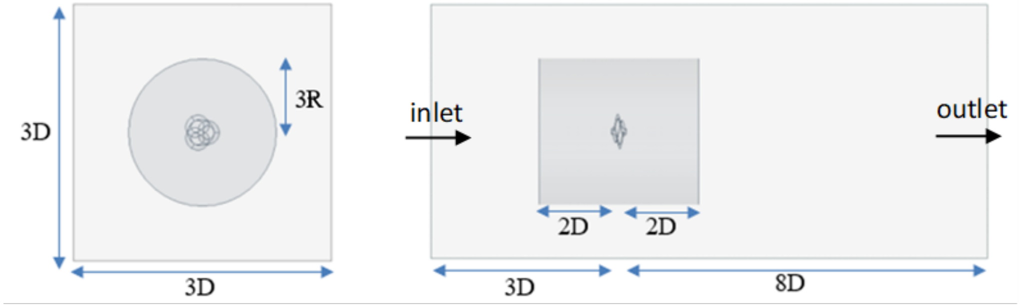

Fig. 8 The numerical domain model for the performance analysis (a) front view (b) side view.

Results and Discussion

The initial performance of the turbine was investigated at a pitch angle of 0°. The numerical analysis produced showed that the turbine performed optimally at a $C_P = 0.24$ at a $TSR = 4$ whereas the thrust coefficient of the turbine reached a maximum value of 0.29.

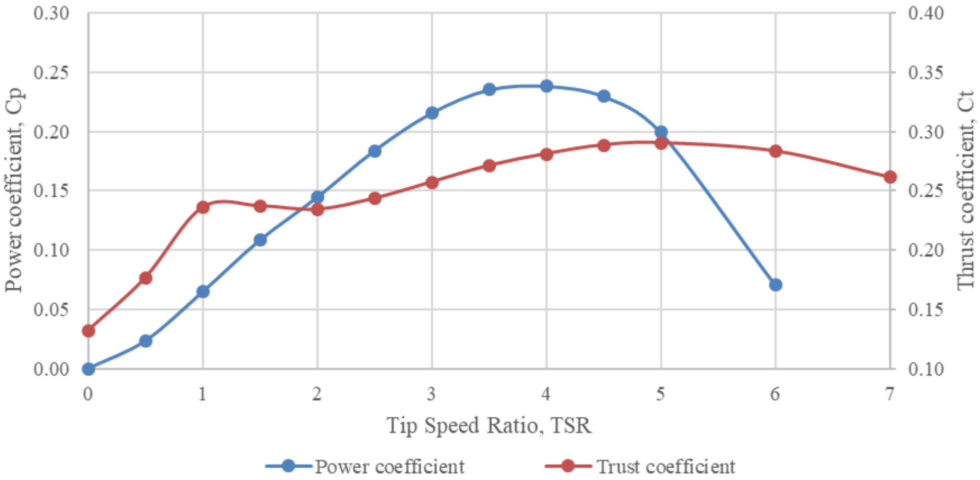

Fig.9 Power and thrust coefficient performance of the turbine against TSR.

The full range of the operational TSR is between 0 < TSR < 6.5. In comparison, a generic horizontal axis tidal turbine has the optimal C_P of more than 0.4 with the optimal TSR at around 6 and a full range of 0 < TSR < 12 [10]. It supports that the turbine operates optimally at a lower TSR albeit at a lower C_P.

Summary

This study shows the procedure for designing a tidal turbine for low velocity application by generating five conceptual designs based on the literature reviews. Appropriate criteria for the matrix were carefully selected to represent the production, installation, and operational conditions of the turbine. The finalised design i.e. Design 1 was further analysed using numerical model was conducted to investigate the performance of the turbine. It was found that the turbine operates optimally at a C_P of 0.4 at TSR = 4.

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