Chapter 2
Review of Current Trends in Marine Energy: Large Tidal Current Turbines

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Abstract The world is making its transition to sustainable renewable energy. Researchers have studied the behavior of tidal current turbines (TCT) under various conditions as well as numerous approaches for application. Using Betz limit theory, many studies were conducted to analyze the usage of TCT and modification of TCT for all the living things without affecting the environment. With regards to the design development of TCT, the various technological trends such as yaw drive mechanism and horizontal axis turbine have been discussed. The paper has reviewed the latest update on various TCT energy generation capacities by different companies at differing locations.

Keywords Marine energy · Tidal current turbine · Renewable · Sustainability

2.1 Introduction

The world is making a shift from energy sources that release greenhouse gases to renewable energy sources. Many countries via their respective organizations have already set roadmaps to slowly transition to higher reliability on renewable energy sources such as the European Union [1], ASEAN [2], G20 [3] and the UAE [4]. According to the Institute of Renewable Energy, IEO in year 2020 renewables are projected to be the dominant energy supply by 2050 at the current trajectory of increased global energy consumption of 50% by 2050, a 3% global GDP growth per year and a 0.7% global population growth per year. There is a plethora of renewable energy sources available, where the more commonly known ones are photovoltaic (PV) cells, wind turbines, hydroelectric or nuclear plants, etc. The less commonly known which has the potential for scalability is based on tidal current turbines. A tidal current turbine is a subset of marine energy generation.

When a certain individual makes a recreational visit to the beach, the idea that crosses one's mind is the serenity of the sound produced by the crashing waves.

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However, to the engineer, this sound of crashing waves is the sound of wasted unharvested energy produced by ocean. The tidal current turbines (TCT), also known as underwater turbine, marine current turbine and tidal stream generator are similar to concepts of wind turbines; however, instead of air moving the blades of the turbine, the seawater is replaced as a medium.

Alternative versions of TCT such as wave generators are also able to generate electricity. However, the eye sore produced by large civil and mechanical structures in the middle of the sea can be a predicament. The tidal current turbine is able to overcome this predicament as the turbines are installed underwater and at the seabed. Energy is generated through movement of the TCT blades by moving seawater attributing to changing tides. This movement is highly predictable; which is a result of the earth-Sun astronomical tide (known as solar tide) and earth-Moon astronomical tide (known as lunar tide). This predictability makes the tidal current a more reliable source as compared to solar and wind energy [5]. Reliability and predictability are an important factor in power generation so that the existing power grid running on non-renewable energy sources is able to adequately supplement the power generated to prevent an electricity blackout. When wind speeds are low or during a cloudy day, the electricity generation from these renewable sources is low. This will cause a power consumption spike in the electricity grid which can be harmful. On top of that, wind fluctuation affects voltage and frequency quality with their large deviations [6].

2.2 Betz Limit for Turbine Efficiency

The German physicist Albert Betz produced a law that applies to all Newtonian fluids, which states that the theoretical maximum efficiency of a turbine is 16/27 or 59.3% [7]. Recent theoretical framework has proposed that unsteady flow is able to surpass the Betz limit [8]. On the other hand, Young [9] states that in practice, a single foil system will not exceed the Betz limit even in unsteady flow effects. The Betz limit is commonly applied in the design of wind turbines. However, because air and water are both Newtonian fluids, therefore, for TCT, the Betz limit applies as well. According to the study of the Betz limit in wind turbines, the velocity of air drops as it passes through the turbine. Thus, 100% of the energy cannot be absorbed by the wind turbine allowing the wind flow through the exit of the turbine. When wind stops moving at the exit of the turbine, no fresher wind could get in [10].

Betz's law also states that as wind velocity decreases due to the loss of energy by the extraction from a turbine, the airflow must distribute to a wider area. Betz's law also states that as the rotational speed of the turbine blade increases, the blockage of the flow increases. This means that faster rotating turbine blades do not necessarily indicate more power generation [11]. For each speed of medium, there is an optimal rotational speed that maximizes the generation of power. The tip speed ratio as shown in Eq. (2.1), which is the velocity at the tip of the blade, must be constant.

$$\text{tip speed ratio} = \frac{\text{velocity of the blade}}{\text{velocity of the water}} = \frac{\omega r}{u} \tag{2.1}$$

where w is the rotational speed of the blade (rad/s), r is the radius of the blade (m), and u is the initial velocity of the turbine (m/s).

At low velocities of water of 0.4–0.8 m/s, the tip speed ratio should be increased to increase the coefficient of performance, Cp for energy generation [12]. The Betz limit, however, can be overcome by placing a turbine in a duct. However, this is still under discussion [13]. On top of that, studies have shown that an optimally blocked channel with turbines can increase the Cp of the Betz law by eight times [14].

2.3 Tidal Current Turbine (TCT) Conditions

The arrangement of the turbine depends on four important factors which are the blockage ratio, the tidal current turbine (TCT) horizontal distance, the tidal channel cross-section and the power fluctuations.

2.3.1 Turbine Arrangements for Tidal Current Turbine

A few studies have proposed the arrangement of multiple turbines arranged to increase the efficiency of the tidal current turbine. This is also known as farm arrangement. Arrangement patterns include double row centered (also known as double row parallel or double row fence) and double row staggered [15]. The turbine arrangement depends on the features of the tidal channel. If the channel is long but narrow, multiple staggered layouts are suitable [16]. The best arrangement for TCT in a tidal channel depends on the blockage ratio of the TCT. No two tidal channels are the same across the width and length as most seabeds have uneven floors.

2.3.2 Horizontal Distance Between Turbine Rows

Ouro et al. [17] discovered that when the horizontal distance between two rows of turbines is too near, at 4D (4 times the diameter of the rotor), the wake of the flow causes the velocity of the water to be reduced as it enters the turbines of the second row. Therefore, the adequate horizontal distance must be prioritized to ensure that the flow of the fluid that is entering the second row of turbines is fully formed and free of vortices. This is because, the efficiency of the turbine decreases when the turbine rows are placed too near to each other. It is imperative to ensure that the turbines have the adequate spacing between the adjacent rows so that the downstream turbines can benefit from the great tidal flow velocity recovery [18]. On top of reduced efficiency, lack of horizontal spacing between turbine rows can increase the stress acting on the blades of the second row of turbines at 4D. Vortices produced due to insufficient horizontal distance can cause unsteady loading on the blades, thus leading to premature failure [19].

2.3.3 Tidal Channel Cross-section

The peak flow through the channel is reduced by 71% of the initial value. When considering the flow from one end of a sea channel to another, the maximum average power produced is between 20 and 24% for a sinusoidal tidal head at its peak. The maximum average power does not depend on the location of the turbines along the channel [20]. On top of that, the model requires that the entire channel is blocked by the turbines, which is improbably; thus, the power produced would be further reduced in this case. Few turbines are only needed in a small cross-sectional area where the currents are the strongest because the increase in the number of turbines in a small cross-section can choke the flow [21].

2.3.4 Power Fluctuations and Design

Power fluctuations can occur that will affect the efficiency of the TCT. This is due to stream shear acting on the turbine blade. This problem was theorized to be magnified due to the large rotor diameter and two-blade design of the turbine system implemented [22]. Therefore, the turbine may experience severe periodic fatigue loads. Morandi et al. [23] showed that a high number of inflow kinetic energy (approximating 13–15%) tends to be displaced outside the rotor disk through experimentation. These are inflow power lost in the radial and tangential components. Ergo proposed a second counter rotating rotor of slightly larger diameter could be useful to recover the lost inflow kinetic energy [23].

2.4 Mechanical Properties of Composite Tidal Current Turbine

Growing priority is assigned for developing and promoting renewable energy technologies. The capacity for fine energy within tidal currents is a renewable source of energy. Wherever an effective way can be enhanced to obtain this capacity [24], tidal streams can be used to better meet the increasing energy requirements of the planet. Several studies have verified the great potential of marine current as a predictable, renewable resource for the development of energy on an industrial scale. The use of marine urgent turbines for electrical electricity generation has grown, and the horizontal axes of marine turbines are one good solution for this reason. Many types were considered and evaluated for hydrokinetic turbines, metal materials or composites. Composites have been produced in marine structures, particularly for offshore use. Composite technologies provide new possibilities for maritime and submarine clean energy. In addition, flood effects and seawater sprinkling can be experienced in the aquatic environment [24]. Composite materials play a vital role in the production of marine renewable energy converting systems under extreme environmental conditions. For the hydrokinetic nozzle turbine, these materials are employed. Its attractiveness, including lightweight, high strength and excellent corrosion resistance, makes it the perfect alternative for hydrokinetic designers compared with metallic materials. These criteria dictate the use of composite laminate materials like glass or polymer-reinforced carbon fibers. Efforts to monitor the actions of turbine-based composites have been produced in recent years. The study of impact on induced damaged composites for turbine pads. The components are composed with composites of glass fibers. The force interaction, distortion and damage to the delamination following dynamic loading were studied by the development in Abaqus/Explicit software of three-dimensional finite element models. To measure the initiation of a progression of injury, stress parameters and mechanical fracture techniques were employed. The technique of construction focused on the design of harm mechanics for the composite tidal turbine blades was explored by Fagan et al. [25]. The numerical model is based on Puck's phenomenological fiber failure parameters used in the user-defined 3D shell subroutine. Due to the difficulty of morphology in matrixes, on the other hand, some research studies have included several modes for matrix failure criteria. Different models of failure parameters were modified and used for the prediction of damage to laminate composites [26]. In the work of Mahfouz et al. [27], a 3-m long sea turbine blade made up of composites with polymeric foam as the center's foundation and carbon-epoxy as the face layer is tired and damaged. The technique for fatigue and damage management of the ocean turbine consisting of glass fiber enforced polymer composites is proposed by Kennedy et al. [28]. It is necessary, therefore, to research the damage to laminate composites and delamination, particularly when the turbines are mounted in the marine environment.

2.4.1 Structural Analysis and Development

The sophistication of structures such as marine structures for renewable energy makes the study of dynamic reaction and kinetics of damage of composite structures under impact not easy and sometimes even impossible. Present solutions are of course best suited to such modeling, including numerical codes and explicit approaches. It is simulated that lightweight composites can be incorporated into the ocean program. It is important to present data explaining the behavior of the system to accurately model our structure. They may derive from various sources: materials, geometry, boundaries, loads and interaction with the affected organisms.

2.4.2 Structure and Materials

A 3D structure of the turbine is then created using the Helical software and the FE code Abaqus. The nozzle has an overall diameter of 20 m in the present case. The effect experiments have been performed to provide a superior configuration and the behavior of the hydrokinetic turbine under dynamic pressure. A different impact load was placed on the composite marine turbine structure. Two types of impactor structures, including hemispheric and flat, have been taken into consideration. The effect of impact velocity and impactor structure is studied in a parametric analysis. In modeling the impactor, it is presumed that the module of Young is static and endless [26].

2.4.3 Boundary Conditions

The high density of seawater and unintended impacts on how the marine turbines work are exposed to critical loads. Composite materials are a tremendous advantage because of their outstanding mass/resistance and mass/rigidity connections to satisfy the needs of producers of tidal current turbines, which are usually related to mass gain problems. A hydrodynamic study of the turbine nozzle was used to develop a panel method software in conjunction with the blade factor momentum theory (BEM). The resulting hydrodynamic pressure was then used to predict the initiation of harm under border conditions of the FE code and the Hashin criteria. The loads arising from running water toward and around our punch mechanism are hydrodynamic loads.

2.4.4 Turbine Maintenance

Maintenance is a crucial component of TCT, and thus, certain expectations are to be taken into account. Firstly, ease of replacing the TCT structure. The ability to replace a heavy turbine in an efficient way is always preferred as the cost of installation is high. Secondly, cavitation corrosion also plays a big part in the lifespan of the turbine. This is due to the inability of metal to withstand corrosion. TCT has to deal with certain challenges associated with maintenance, loading conditions, installation, electricity transmission, as well as environmental impacts in order to achieve economic requirements [29]. Operation of TCT should be monitored closely. This is due to the high maintenance cost if an error is not detected during the early stage

[30]. The operation and maintenance cost per unit is calculated by Eq. (2.2).

$$\text{operation and maintenance cost} = \frac{\Sigma(\text{omci})}{\text{energy}} \tag{2.2}$$

where omci is the operation and maintenance cost per year and energy is the lifetime energy output of the whole farm.

2.4.5 Rotor Blade Maintenance

Tidal turbines are able to generate clean and renewable energy. The anticipated service life of the turbines is twenty years [31]. The most important piece of the entire structure is the turbine blade. Reinforcing critically loaded sections of the blade in order to improve longevity and upgrading the blade to achieve higher efficiency are both critical matters. The rotor blades' function is to reap the kinetic energy from the water flow and channel it toward the generator. The blade is able to rotate due to the water current hitting the surface of the blade. The latest designs of tidal turbine have variable pitch in order to adjust according to the water current. Apart from that, the turbines are able to rotate in both directions via bidirectional blades. This feature enables the turbines to harvest the maximum amount of energy, thus increasing the overall efficiency [32]. The material that makes up the blade is also crucial because not all materials are able to withstand the stress that act on the TCT during abnormal loading conditions. It is also found that glass fiber reinforced polymers (GFRP) and carbon fiber reinforced polymers (CFRP) are materials used to fabricate rotor blades for tidal turbines. On the other hand, Chen and Lam [33] found that GFRP and CFRP are less suitable due to their inability to endure harsh weathers, therefore resulting in a low service life. More research is required in the field of material as well as dynamics of the tidal turbine in order to enhance the service life of the rotor blade. As for now, research has proven that heat and water will contribute to the performance of carbon fiber reinforced polymer (CFRP). Firstly, based on the total water that is absorbed by the composite. Secondly, the overall temperature and exposure time of the material. Finally, the sort of polymer utilized as a matrix material [31].

2.4.6 Ability to Withstand Corrosive Saltwater

The corrosion of metal contributes greatly to the economic loss as well as the social harm in daily life and production. Approximately, one-third of the metal scrap in the world accredited to the corrosion of metal. Around 2–4% of a country's GDP is also affected due to this issue. This loss is six times more than the losses caused by typhoons, floods, earthquake and other natural disasters [34]. Saline water, also known as saltwater, is from the sea. Seawater has a salinity of 3.5%, which means for every kg of seawater, approximately 35 g of dissolved salt [35]. When comparing seawater with fresh water, saltwater is able to corrode metal five times quicker than fresh water [36]. Apart from corrosion, saltwater also consists of bacteria that are able to consume iron and turn their excretion into rust. The conductivity and oxygen content of water are directly affected by the salt content [37]. Most materials are weak against saltwater as they corrode within a short period of time. In which, it is not suitable for constructing turbine blades. With regards to the ability of the turbine blade to resist the corrosive saltwater, black anticorrosive coating can wear out after six months of deployment, and the internal composite material becomes uncoated [38].

2.4.7 Corrosion Protection Against Seawater

Material selection should be the most important aspect to ensure long-term safe performance of the turbine. The changes of mechanical, chemical and physical properties of the material should be properly analyzed. Apart from that, new technologies have developed to pay attention and improve on effects caused by contact of metals and corrosive medium. For example, surface coating and treatment technologies can accomplish corrosion protection by coating metal with a non-metallic coat [39]. Other methods such as cathodic protection are also used in order to protect the metal from corrosion. This method utilizes an electrochemical process to protect metal from corrosion. By enabling cathodic polarization via providing current, the potential of the metal turns to negative. The cathodic protection method is also known as the sacrificial anode cathodic protection [40]. Adding small chemicals to the corrosive media is known as the corrosion inhibitor method. This method relies on the physical or chemical reaction in order to slow down the rate of corrosion. All these are accomplished while maintaining the physical, chemical as well as the mechanical properties of the metal. This method is one of the most convenient and low in cost methods used to prevent corrosion [41].

2.5 Conclusion

Current trends in marine energy harvesting are still in its developmental stages. Apart from carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymers (GFRP), new materials are being researched in order to improve the service life of turbine blades exposed to saltwater. The location of the turbine is also a crucial factor as not all sites have a continuous tidal flow with suitable flow velocity. In order to reduce the maintenance and operation cost, placement of the tidal turbine farm should be near the shore.

The layout (positioning) and planning of the turbine farm play a big role in the efficiency of the farm as this may affect the future development if not planed accurately. The layout design for a turbine farm for maximum energy harvesting depends on a plethora of factors which include blockage ratio, horizontal distance between turbine rows, tidal channel cross-section; all of which have been discussed.

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