# A Review of Tidal Current Turbine Technology: Present and Future

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*Abstract*—**Tidal energy is predictable, which makes it highly attractive from the grid integration point of view. Recent years have seen the growth of the tidal current turbines over the traditional tidal range technology. This is primarily because of the success of the wind turbines, which are in principle similar to the tidal current turbines, and the high cost and environmental impacts of the tidal range systems. This paper provides a brief review of the available and proposed solutions for the tidal current turbines. The idea is to give an overview of the different types of technologies involved in the tidal current energy conversion systems, rather than giving a summary of the different market solutions. The paper concludes by highlighting the major challenges faced by the tidal current turbine industry, and an indication of the current trends in the industry.**

***Keywords***—**State-of-the-art tidal current turbines, rim-driven and pod configurations, flooded generators, mounting of tidal turbines, floating platform for converters.**

## I. INTRODUCTION

The adverse impact of burning fossil fuels on the climate has been a big driving force in the development of the renewable energy. A main drawback often cited against the major renewable sources of energy, such as solar and wind, is their lack of predictability, which is highly relevant for their successful grid integration. The predictability of the tidal energy makes it highly attractive despite being relatively expensive at this stage.

According to Zhou *et al.*, the estimated global energy potential of the tidal currents is about 75 GW, with approximately 11 GW being concentrated in Europe [1]. Another estimate puts the global tidal energy potential at about 120 GW [2]. Tidal resources in Europe are mostly located in the United Kingdom, France, Ireland and Norway [3].

Despite the large potential for harvesting energy from the oceans, it has remained relatively under-exploited. The challenge of acquiring substantial finances to drive the growth in this sector has been a major bottleneck due to the risks posed by the marine environment. The risks to the equipment are mainly due to the extreme weather conditions, corrosion and fouling. Furthermore, deploying large-scale energy conversion devices in the sea could have adverse impacts on marine ecosystems. Therefore, the need of the hour is to explore solutions which are not only cost-effective in the long run, but also have minimal impact on the marine ecology.

Tidal energy can be exploited in two ways, namely, the tidal range and the tidal current turbine technology. The former resembles the hydroelectric generation in that it uses the potential energy of the water, stored at a suitable head. On the other hand, the latter is akin to the wind turbine technology, as it converts the kinetic energy in the tidal flow to electrical energy.

Despite being developed first on a larger scale, tidal range technology has fallen behind the tidal current turbine technology. The main drawbacks to the tidal range technology are its high capital cost and the likely adverse environmental impacts. Tidal current turbine technology is currently at a lower level of technological readiness compared to the tidal range technology. But, because of the likelihood of the lower cost of energy, and of minimal impact on the local biodiversity, tidal current turbines are likely to be the future of the tidal industry. Most projects in tidal current turbine industry came up in early 2000s. This was partly caused by the support of UK's Department of Trade and Industry (DTI) in 2001, and accordingly UK has been the world leader in this sector [4]. This willingness to move towards the tidal current turbine technology has been driven to a significant extent by the success of the offshore wind industry.

## II. TIDAL CURRENT TURBINES

The most common type of the tidal turbines is the horizontal axis tidal turbine. Besides this, the vertical axis tidal turbines, and other designs including reciprocating-based systems (such as hydrofoils), screw-like devices and tidal kites also exist. Fig. 1 shows an example of a horizontal axis tidal current turbine.

According to Corsatae and Magagna [6], 76% of the research and development investments in the tidal industry is focused on the horizontal axis tidal turbines (HATTs), whereas about 2% went to vertical axis turbines. HATTs have also proven to be more reliable and survivable in harsher conditions [3]. For these reasons, we shall henceforth focus only on the horizontal axis tidal turbines.

## III. CLASSIFICATION OF HORIZONTAL AXIS TIDAL TURBINES

In this section, different technologies used in horizontal axis tidal current turbine power take-off systems are presented. The focus is on classifying them based on the difference in the technology of their basic components, such as the type of generators, the type of mounting of the turbines, and the

Fig. 1 Nova Innovation's M100. Image source [5]

placement of converters. This is done to clearly identify the similarities and differences between different manufacturers. Each classification system is described in the following subsections.

### A. Pod and Rim-driven configurations

Based on the placement of the generator with respect to the turbine, tidal current turbines are of two types: Pod and Rim-driven configurations.

In the pod configuration, the generator is located behind the turbine blades on the horizontal axis. Fig. 1 represents an example of a pod type tidal turbine. Among other factors, the external diameter of the generator is limited to avoid the blockage of the flow across the blades [7]. Manufacturers using the pod type turbines are Nova Innovation, Atlantis Resources, Andritz Hydro Hammerfest, Tocardo, Schottel, etc.

In the rim-driven case, the generator is placed in a shroud surrounding the turbine blades. Fig. 2 shows an example of a rim-driven generator. Here, the internal radius of the generator is constrained by the rotor diameter of the turbine. Higher hydrodynamic efficiency compared to the pod configuration is expected, where the machine volume can affect the water flow across the turbine [9]. The design of reliable and economical large diameter bearing systems is one of the main challenges in this design. DCNS-OpenHydro's Open Centre turbine seems to be the only prominent example of the rim-driven turbine, among the major manufacturers of the tidal turbines [10].

Between 1999 and 2005, Tocardo tested and compared a venturi-duct rim-driven (ring) generator and an open rotor two-bladed direct-drive pod generator. Based on their findings, they concluded that the latter proved more economical than the former [11].

Fig. 2 Rim-driven generator, DCNS-OpenHydro. Image source [8]

### B. Number of Blades

Most pod type horizontal axis tidal turbines either use a 2-bladed or a 3-bladed turbine. According to [3], more than 50% of the horizontal axis tidal turbines use a 3-bladed turbine, whereas only 25% use a 2-bladed turbine; designs using more than 3 blades also exist. Rim-driven turbines generally tend to have more blades than the pod-type turbines.

Advantages of the 2-bladed turbines include low-cost, easy installation, and a higher tip-speed ratio. Higher tip-speed ratios help in reducing the size of the gearbox or the generator. Disadvantages of the 2-bladed turbines include increased wake and cavitation problems due to higher rotational speed, and relatively higher tower effect compared to a 3-bladed turbine. Tocardo's T2 turbine, shown in Fig. 3 is an example of the 2-bladed turbine. Five T2 tidal turbines have already been installed in the Eastern Scheldt storm surge barrier, in the Netherlands [12], and have shown promising success.

A 3-bladed tidal turbine is more popular for larger turbines; they are preferred because of their higher hydrodynamic efficiency, less impact due to the tower, less problems due to the wake and cavitation. Additionally, such turbines also tend to have low cut-in speeds. Furthermore, not much is gained by increasing the number of blades beyond 3, be it in terms of efficiency or stability [13]. Example of a 3-bladed turbine is the Schottel's Instream turbine, shown in Fig. 4.

Number of blades also has a significant impact on the $C_p$-λ characteristics of the turbine. Higher blade number is likely to result in a turbine with a sharper $C_p$ curve and hence, better stall performance. On the other hand, two-bladed turbines usually have a flatter $C_p$ curve to allow operation over a wide tip-speed ratio [15].

Fig. 3 Tocardo T2 turbines. Image source [12]

Fig. 4 Schottel's Instream Turbine. Image adapted from [14]

### C. *Mounting of Turbines*

Basically, tidal current turbines are mounted in four topologies [16], as described below.

1) *Floating Tethered:* Bluewater, in collaboration with various other partners including Tocardo and Schottel, commissioned the BlueTEC floating platform in 2015. The turbine and the generator are submerged, and hanging from the bottom of the platform as shown in Fig. 5. The floating platform is tethered to the seabed and can be easily moored to the shore for overhauling of the system. The platform also houses the power electronic converter and other critical equipment for easy and quick access during maintenance. The platform is still in use to test different turbines and is connected to the Dutch grid in Texel, Netherlands [18], [19].

Fig. 5 Bluewater's BlueTEC Platform. Image source [17]

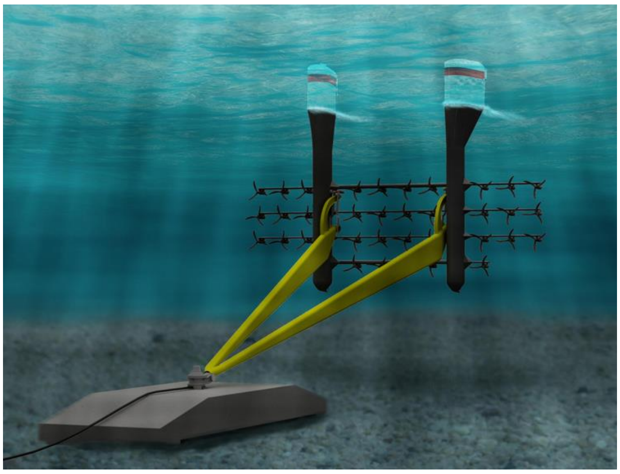

Fig. 6 Schottel's Triton S platform. Image source [14]

2) *Submerged Tethered:* An example of the semi-submerged systems is the Schottel's Triton S platform shown in Fig. 6. The Triton system can have multiple cross arms, each with multiple turbines to allow for redundancy and high power energy capture. Two tether arms hold the Triton to the seabed through a gravity based foundation, besides allowing the Triton to orient itself in the flow direction. Power electronic converters are housed in the floating spar buoys [14].

3) *Seabed Bottom-mounted:* Mounting of turbines near the seabed is good for stability and minimising the turbulence effects compared to the near surface mounting. Fig. 7 shows the Atlantis Resources AR 1500 turbine mounted on the support structure tower held by the gravity based foundation [20]. Other examples include Openhydro's Open centre and Nova Innovation's M100 turbine. This type of foundation does not penetrate deep into the seabed; therefore, no subsea drilling is required.

Fig. 7 Atlantis Resources' AR 1500 turbine. Image source [20]

4) *Seabed Pile-mounted:* Tidal turbines can either be directly mounted on the pile or they may be mounted on the cross arms, which are themselves supported by the pile foundations. For example, under the SeaGen project (from Marine Current Turbines-Siemens), twin 1 MW turbines are mounted on a cross arm piled on a monopile foundation, as shown in Fig. 8 [21].

The surface-piercing steel tower, shown in Fig. 8, can easily allow taking out the turbines out of water for maintenance purposes. This eliminates the need for deploying large marine vessels for maintenance.

Different adaptations of these basic topologies are also implemented, as mentioned in [22].

### D. Fixed-pitch and Variable-pitch

The blades of the tidal turbine are pitched to regulate the power output from the turbine. In cases where the blades cannot be pitched, power control is achieved by the stall regulation. However, this also results in a poorer efficiency below rated speeds. A more recent approach is to use speed assisted stall control [23]. Examples of the fixed pitch system include Nova M100 and Schottel's Instream Turbine, shown in Fig.1 and Fig. 5 respectively [24].

On the other hand, a more active and desirable (in terms of efficiency) control is achieved by pitching the blades. Employing the pitch control increases the cost and the chances of failure, however, for higher power ratings, it's preferred over the fixed pitch blades. Atlantis Resources AR1500 tidal turbine, shown in Fig. 7, and the Andritz Hydro Hammerfest employ a variable pitch control [25].

Around 2012, Tocardo developed and tested its 2-bladed T1 turbine. In this design, both the blades are simultaneously turned by 180° during the slack tides for reverse flow operation [11].

### E. Yaw Control

Yaw control is essentially the orientation control of the turbine main axis. Changing the orientation of the turbine axis, changes the angle of attack with the blades, thereby changing the power coefficient and the thrust coefficient of the blades.

Fig. 8 SeaGen-S (MCT-Siemens) turbines. Image source [21]

Because of the location of the tidal turbines at places where the funnelling effect usually reinforces the tidal velocity, the need for yaw control is not as important, as say in the case of wind turbines. However, since the tides change direction by about 180°, typically every 6 hours, some manufacturers do prefer having the yaw control. An example of such a turbine is the Atlantis Resources AR1500, where the yaw is operated only during the slack tides to face the next incoming tide [20].

Another commonly used approach, instead of using yaw control, is to design the blades with reasonable efficiency in both the upstream and the downstream phases.

### F. Generator Type

Squirrel cage induction machines and permanent magnet (PM) synchronous machines are widely used as generators in tidal turbines. Although PM machines are expensive compared to the electrically excited synchronous machines, the lower failure rates among PM machines make them attractive.

In this subsection, we classify generators into two main categories: high-speed generators with a gearbox, and low-speed direct-drive generators.

1) *High-speed Generators with a Gearbox:* The size of the generator is directly related to its torque rating, which implies for the same power, high-speed machines are smaller. In addition to manufacturing costs, transport and assembly costs are also likely to be lower for high-speed machines. Since, tidal turbines rotate at low speeds, a gearbox is necessary between the turbine and the high-speed generator.

Atlantis Resources AR1500 turbine uses a radial flux surface permanent magnet synchronous generator with a 2-stage epicyclical gearbox [20]. On the other hand, Andritz Hydro Hammerfest HS1000 and Schottel's instream turbine comprises an induction generator with a 3-stage and a 2-stage planetary gearboxes, respectively [24], [25].

2) *Low-speed Direct-drive Generators:* Low-speed direct-drive generators can be directly coupled to the turbine without

the need for a gearbox. This significantly improves the overall reliability and efficiency of the system.

Direct-drive generators usually have high pole numbers, and thus small pole-pitch. This makes PM machines suitable for direct-drive applications because induction machines with high pole numbers result in an inefficient design due to lower power factor [26]. DCNS-OpenHydro and Tocardo T2 turbines, shown in Fig. 3 and 4 respectively, use a direct-drive PM generator.

### G. Sealed and Flooded Generators

Usually, the generators in a tidal current turbine systems are concealed inside a nacelle. This is to prevent the direct contact of the corrosion prone materials in a generator with the sea water, which reduces the risk of failure and the cost of the generator. As an example, consider again the Atlantis Resources AR1500 turbine. In this case, passive cooling of the generator and the gearbox is provided by the sea water via the nacelle frame [20].

On the other hand, a flooded generator is an open-to-sea generator, where the stator-rotor gap of the generator is filled with the sea water. The DCNS OpenHydro's open centre turbine (which has a rim-driven generator), shown in Fig. 3 is an example of a flooded generator. The stator and the rotor active material are encapsulated with a thick non-metallic material to protect against the sea water. Surface mounted magnets and the slotless stator design, further lengthen the magnetic gap, thereby demanding thicker magnets, and increasing the cost significantly [27].

### H. Location of Converters

With respect to the placement of the converters, mainly three possibilities exist.

*1) Onshore Converters:* Experience from the offshore wind industry suggests that the failure rate among converters is much higher than the generators [28]. This has prompted most tidal turbine manufacturers to place converters onshore, giving easy access for frequent maintenance and reducing the cost of energy. An example of this is the Andritz Hydro Hammerfest (AH1000 MK1) and Atlantis Resources (AR1500) turbines used in the Meygen project [29].

*2) Housed in the Nacelle:* Clearly, onshore placement of converters for each turbine in a tidal array will result in huge cabling costs. Therefore, the placement of converters close to the generator is desirable. A simple way to achieve this is by placing the converters in the sealed nacelle alongside the generator. GE's (formerly Alstom) Oceade turbine is an example of this configuration [30].

3) *Offshore Platform Mounting:* To provide an easy and a quick access for the converter repairs, a floating or a pile-mounted surface-piercing platform is often used. An example of each case is the Bluewater's BlueTEC platform and the SeaGen project shown in Fig. 5 and Fig. 8, respectively.

## IV. CHALLENGES TO TIDAL TECHNOLOGY

The challenges to the tidal energy harvesting are not limited only to the complexity and the reliability of the design. Other challenges in the economic exploitation also arise, as mentioned below.

Locations suitable for the economic exploitation of the tidal energy are often far from the grid network. The costs involved in the expansion of the grid or its upgrade at the desired location sometimes is a major bottleneck in setting up a tidal farm [3].

A few tidal turbines are unlikely to cause any detrimental impact on the local biodiversity; this has been concluded by several studies [11]. Even so, it would be too simplistic to draw the same conclusions, without extensive research, for a tidal farm with several tidal turbines. Some projects have undertaken an extensive environmental impact assessment at various stages during their development to study the impact on the local marine life, Meygen project is a case in point [30].

From the economic viewpoint, it is difficult to predict the future of the tidal turbine technology. The success of the prototypes, currently under design and testing, in the field is crucial for encouraging future investments, before economies of scale can take over bringing down the cost of energy.

## V. CONCLUSIONS AND FUTURE

Despite the maturity of the tidal range technology, the capital cost and the environmental impact involved with tidal ranges has almost entirely shifted the focus towards the tidal current turbines. Tidal turbines are currently at a lower technology readiness level (TRL) than offshore wind, partly due to the additional challenges of operating in a subsea environment. However, the potential benefits of this predictable energy source provide a strong driver to push this technology forwards towards maturity.

Frequent maintenance required in the gearboxes, resulting in high O&M costs, has prompted a trend towards the direct-drive generators. The design and costs for the direct drive generators should be carefully investigated; larger diameter of the generator can impede the flow of water, reducing the efficiency. Moreover, the cooling properties of the sea water should be exploited as much as possible to reduce the generator cost, and increase its lifespan. Flooded generators could prove to be a promising alternative in this direction. Furthermore, the use of fault-tolerant multiphase PM machines or double stator PM machines must be investigated for improved reliability [31], [32].

For large scale tidal current farms, onshore converters are impractical. Therefore, power electronic converters housed in a subsea nacelle, or mounted on the floating platforms or on the surface piercing foundations are being explored. Because of the high failure rates in converters, it is imperative to investigate and design converter topologies which result in the longer expected lifetimes. This can be achieved by overrating of components, or implementing topologies which do not unequally stress switches, thus preventing an early failure. The design of converters should be carried out in conjunction with the generator to decrease the levelized cost of energy from tidal turbines.

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