

## Vertical Axis Tidal Current Turbine: Advantages and Challenges Review

Dendy Satrio,<sup>a,\*</sup> I Ketut Aria Pria Utama,<sup>b</sup> and Mukhtasor,<sup>c</sup>

<sup>a</sup>Doctoral Student at Ocean Energy Engineering and Management, Institut Teknologi Sepuluh Nopember, Indonesia

<sup>b</sup>Naval Architecture and Shipbuilding Engineering, Institut Teknologi Sepuluh Nopember, Indonesia

<sup>c</sup>Ocean Engineering, Institut Teknologi Sepuluh Nopember, Indonesia

\*Corresponding author: [dendy.satrio15@mhs.na.its.ac.id](mailto:dendy.satrio15@mhs.na.its.ac.id)

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### ABSTRACT

Tidal current energy conversion technology has been proposed by many researchers and companies as a solution for power generation. Until today, the technology is still at stage of research, development and field testing before it can reach a successful commercial stage. This study is conducted by reviewing published papers. Based on literature review, horizontal axis tidal current turbines have higher efficiency and have been developed by many renewable energy companies in the world. However, vertical axis tidal current turbines indicate opposite situations. The vertical type possesses some advantages that are cheaper in production, easier in installation because the generator can be placed on top, suitable for floating systems and others. It is applicable for some developing countries considering the capabilities of production technology and marine environment's conditions. Therefore, the current study discusses about the advantages and the challenges that must be answered on vertical axis tidal current turbine development.

**KEY WORDS:** *Renewable energy, tidal current, vertical axis turbine, power generation.*

### NOMENCLATURE

$A$  Cross-Sectional Area ( $m^2$ )

$C_p$	Coefficient of Performance (%)
$D$	Diameter of Rotor (m)
$H$	Height of Rotor (m)
$P$	Power (Watt)
$RPM$	Revolutions Per Minute
$v$	Free Stream Velocity of Water (m/s)
$\pi$	Phi (3.14159)
$\rho$	Density of Water ( $kg/m^3$ )

### 1.0 INTRODUCTION

Energy demand always increases, particularly electrical energy. This is due to population growth, economic growth, development of industries, technological advances and rising standards of living in the society. Global primary energy consumption in 2008 was 143,851 TWh consisted of 81.2% from fossil fuel (oil, coal and natural gas), 12.8% from renewable sources and 5.8% from nuclear power [1]. World electrical energy consumption has been projected to grow by 2.5% per annum between 2008 and 2035 from 16,819 TWh to 32,922 TWh, assuming that current energy policies remain unchanged [1]. Unfortunately, most of the energy sources that are used to generate electricity are fossil fuel energy.

Fossil energy is a debateable conventional energy in recent years. In addition, its availability is dwindling and it can not be renewed. Fossil energy produces pollution that can contaminate environment. Fossil energy usage also causes climate change. Therefore, all people around the world makes many efforts to replace fossil energy to renewable energy. Renewable energy sources are more environmental friendly than the conventional energy sources [2].

Renewable energy can be extracted from variety of natural resources. One of them can take advantage of energy source from water. Hydropower is the cheapest and the biggest energy source in the world [3]. World electrical energy needs of approximately

18% is supplied by hydropower [4]. This energy is very promising because its abundant availability, environmental friendly technology and easy enough to harness it.

Basically, hydropower principle can be obtained in two ways, namely, potential energy (hydrostatic) and kinetic energy (hydrokinetic) from water [5]. Explanation about the difference of those principle are discussed in the next section. This study focus on kinetic energy types which stored in the water stream.

Water stream or water current sources can be divided into four categories, they are from river, tidal, ocean and other artificial canals [6]. This study investigates hydrokinetic energy from tidal, specifically tidal currents. The current movements of seawater are dominantly driven by changing tides.

Hydrokinetic technology before reach pre-commercial stage must go through some further advancement stages. These stages are research, development and field testing. Resource assessment of ocean current energy has done in Bay of Fundy (Canada) [7]. Preliminary study of tidal power generation pilot project in Alas Strait (Indonesia) also show that some developing country has a promising energy source [8]. Le et al. [9] compared performance of helical and straight blade turbines. In addition, Bahaj et al. [10] also did research with experimental method about power and torque measurements. Other similiar studies are still remain to do for obtaining hydrokinetic technology with better performance. Furthermore, project development and field testing have done in Bay of Fundy and Puget Sound (Whashington) [11, 12]. Some organizations also start for making standards and references, such as EPRI [13], the US Department of Energy [14], the National Hydropower Association [15] and EMEC [16]. In recent years, many people from different sides of diciplines take participations of hydrokinetic technology development in various stages.

Hydrokinetic energy conversion system is an integrated system of some components that has function to extract kinetic energy of water into electricity as final energy. The early conversion process begins when the kinetic energy of water converted into mechanical energy. This process is very important because it determines the overall efficiency of the system. The component used is hydrokinetic turbine [17].

Classifications of hydrokinetic turbines based on rotation of the axis are divided into three types: horizontal-axis turbine, cross-flow turbine and the vertical-axis turbine [17]. The types that have been many developed are horizontal axis (43 %) and vertical axis (33 %) [17]. Horizontal-axis turbine has higher efficiency than vertical-axis turbine. Many renewable energy companies around the world develop horizontal type because it has proven performance results. Some companies developing this horizontal type are Free Flow [18], Marine Current Turbine [19], Hammerfest [20], Lunar Energy [21], UEK [22], Open Hydro [23, 24] and others. Horizontal axis type are more quickly reach commercial stage because refer to wind turbine industries that already widely applied horizontal axis types.

Vertical-axis turbine has lower efficiency than horizontal type [25]. But, vertical type has several advantages that are interesting to develop. The advantages of vertical-axis turbine are cheaper in production, easier in installation because the generator can be placed on top, suitable for floating system and others [17, 26]. Other advantages possessed discuss in the next section. However, there are some drawbacks to be overcome. Some developing countries have promising tidal current energy sources, such as Indonesia. Indonesia has practical potential energy of tidal

currents about 17.9 GW [27]. Therefore, the current study discuss about the advantages and the challenges that must be answered on hydrokinetic turbine especially in vertical axis type of tidal current turbine.

## 2.0 HYDROKINETIC ENERGY CONVERSION SYSTEMS

There are two principle ways to harness energy from hydropower, namely, potential energy (hydrostatic) and kinetic energy (hydrokinetic) from water [5]. Hydrostatic is a conventional way to convert potential energy from water for producing electricity. Khan et al. [17] use term of hydroelectric. Firstly, we must build a dam or reservoir to store water in abundant amount. Reservoir and power house are connected by penstock. Reservoir must be located higher than power house for making a pressure head to generate potential energy. Inside the power house, there are some main components, those are turbine, generator and other electrical component to control output power. Before storing water to the reservoir, there is pathway of water stream which is collecting water from rivers. The building of water dam and water pathway can cause environmental effects. Large scale of hydrostatic power plant has some unfavorable effects on the environment such as people relocation, inundation of agricultural, historical and habitat areas, sedimentation of fertile lands, methane (CH<sub>4</sub>) gas emission, altering the river regime and others [5].

Hydrokinetic is an unconventional way to convert kinetic energy from water. The kinetic energy inside the water stream is directly converted into electricity by relatively small scale turbine and coupled with generator without impoundment which almost no head [3]. Hydrokinetic turbines are also called free flow turbines, ultra-low or zero head hydro turbine [28]. The kinetic energy is contained in water current or water stream. Basically, its sources can be divided into four categories, they are from river, tidal, ocean and other artificial canals [6]. Artificial canals are man-made waterways or channel from drains factory. This work focus on investigating hydrokinetic energy from tidal or ocean, especially tidal currents. Ocean currents are constant flow of seawater around the ocean. These currents are driven by wind, water temperature, water salinity and density amongst other factors. Tidal currents come from local regular diurnal or semi-diurnal seawater flows caused by the tidal cycle. The current movements of seawater are dominantly driven by changing tides. This an unconventional way is being recognized as a new interesting solution that need to be developed.

Hydrokinetic energy also can be distinguished as in-land water resources (river or artificial canal) and marine energy resources (ocean currents or tidal currents). Yuce et al. [5] classified marine energy resources into two types, namely, current energy conversion systems (CEC) and wave energy conversion systems (WEC). In last two decades, marine energy resource is one of the fastest and the newest growing sector in renewable energy [29]. Most of the technologies are at the state of research and development, there are few devices at the pre-commercial development stages [30]. CEC itself is classified into four types, specifically horizontal-axis turbine, vertical-axis turbine, helical turbine and ducted turbine [5]. This study concern in CEC and especially in vertical-axis turbine.

### 2.1 Conversion Schemes

The kinetic energy contained in tidal currents changes become electrical energy through several stages of energy conversion processes. Figure 1 show an outline of a hydrokinetic energy conversion system. First energy conversion process from kinetic energy of water stream converted to mechanical energy is used vertical-axis turbine (the turbine type base on example at Figure 1). After that, mechanical energy is transmitted by vertical axis shaft then coupled with generator. Inside the generator there is conversion energy schemes from mechanical energy to electrical energy. The generator will produce electrical energy at certain RPM (usually in high RPM). However, hydrokinetic turbine produces low RPM. Instream Energy Systems [31] make a 25 KW Hydrokinetic Turbine with rate water velocity 3 m/s that can produce 30 RPM. RITE project also inform that turbine rotates slowly approximately 35 RPM [32]. Hence before turbine couple with generator, an increasing gear must be applied for reach rotation at certain RPM according to specification generator used. Finally, electrical energy is transmitted to the society by grid connection. However, before it transmitted, there are some electrical component (power converter and control systems) which are passed to ensure that the output power stable.

The kinetic energy sources contained in tidal currents depend on current velocity, density of the fluid and cross-sectional area. The production of electrical energy as final energy depend on efficiency of each energy conversion process. They are hydrodynamic, mechanical or electrical process. Therefore, some researchers and developers try to optimize each energy conversion processes to achieve better final energy.

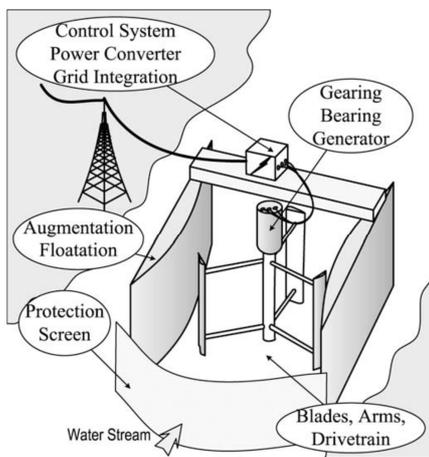


Figure 1. Outline of a hydrokinetic energy conversion system [28].

Equation for calculation output power of tidal current turbine is analogous to that of wind power equation [33]. There is power coefficient ( $\eta$ ) that functionate to be times factor for reducing available power. Power generated from tidal current is:

$$P = \eta \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \quad (1)$$

Cross-sectional area (A) for horizontal-axis turbine can be taken as swept area of the rotor.

$$A = \frac{1}{2} \cdot \pi \cdot D^2 \quad (2)$$

And cross-sectional area for vertical-axis turbine is equal to height of rotor (H) times with rotor diameter (D).

$$A = H \cdot D \quad (3)$$

There is theoretical limit coefficient of performance for horizontal-axis turbine. That is about maximum power extracted from tidal currents. This limit is similar case to the wind turbine. It is best known as Betz limit. Betz limit is 16/77 or equal with 59.3% for single and open actuator disc [34, 35]. That become a common practice to use it for estimating energy of such turbine [17]. While for vertical-axis turbine, this limit is 16/25 or equal with 64% [36]. Practically, hydrokinetic turbine with low mechanical losses is approximately 30% [37]. For better design system, the overall coefficient of performance is between 40% and 45% [38].

### 2.2 Hydrokinetic Turbines Classification

Khan et al. [17] classified hydrokinetic turbines based on rotation of the rotor axis into three types: horizontal-axis turbine, cross-flow turbine and vertical-axis turbine, show at Figure 2. They also recorded and studied about 76 systems, the result show that horizontal axis (43%) and vertical axis (33%) are more interesting to research and develop [17].

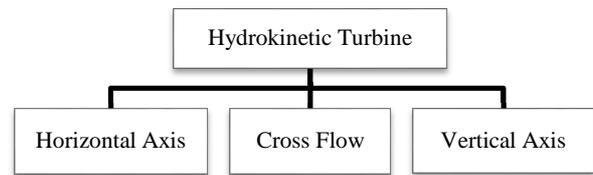


Figure 2. Classification of hydrokinetic turbines.

Horizontal-axis turbine is also known as axial-flow turbine. This type has rotor axis parallel to the tidal currents and employ propeller type rotor. It harness lift force to rotate the rotor. Cross-flow turbine has rotor axis orthogonal to the tidal currents. This type is also known as water-wheels. It is mainly drag based device. Vertical-axis turbine has rotor axis normal to the tidal currents. This type uses lift or drag force to rotate the rotor. Detail explanations about vertical axis type are at the next section. Some examples of the technology that have been developed by industry are illustrated at Figure 3.

For horizontal-axis type, there are Free Flow (three blades), SeaGen (double two blades) and Open Hydro (multi blades) [18, 39, 24]. For vertical-axis type, there are Instream Energy System (mounting structure), Kobold (floating structure) and Lucid Energy (in pipe structure) [31, 40, 41]. For cross-flow type, there are Atlantisstrom (single turbine) and Tidgen (multi turbines) [42, 43]. Each company try to innovate in developing hydrokinetic energy technology.

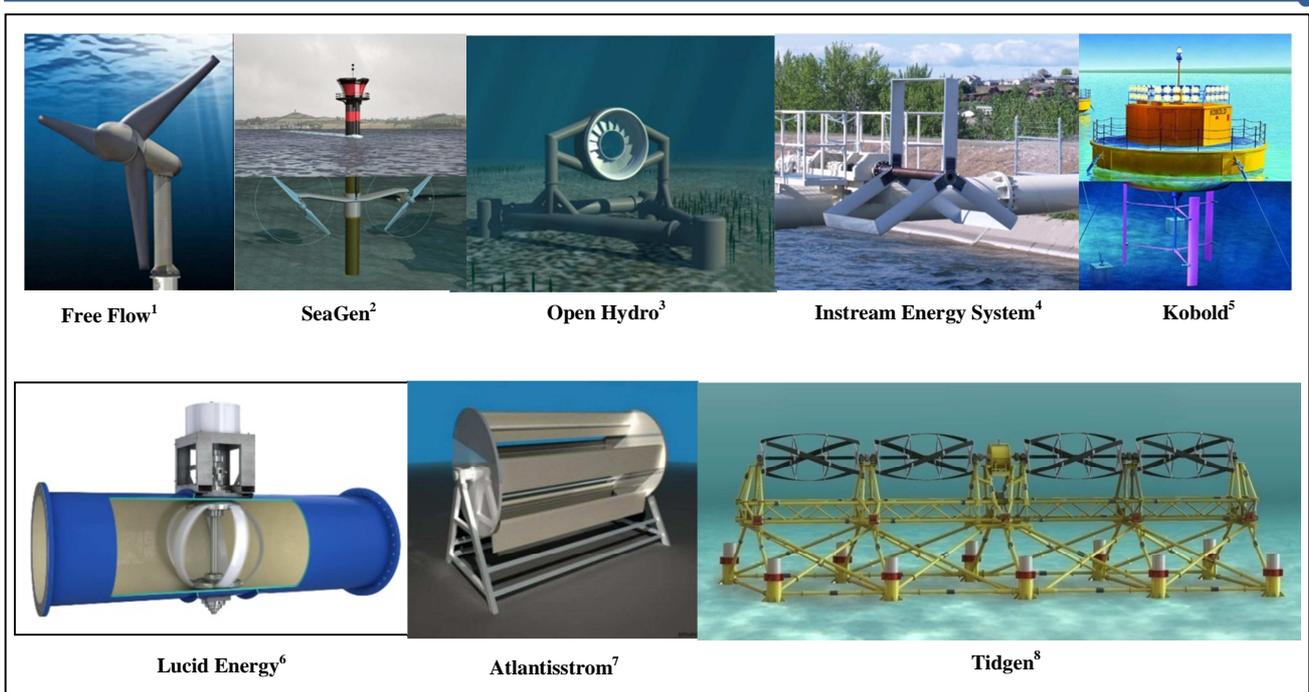


Figure 3. Some examples of hydrokinetic energy. Image references: <sup>1</sup>[18], <sup>2</sup>[39], <sup>3</sup>[24], <sup>4</sup>[31], <sup>5</sup>[40], <sup>6</sup>[41], <sup>7</sup>[42], and <sup>8</sup>[43].

Khan et al. [17] also classified hydrokinetic turbines base on rotor placement options. There are three mounting options, namely, bottom structure mounting (BSM), near-surface structure mounting (NSM) and floating structure mounting (FSM) [17]. Those are illustrated at Figure 4.

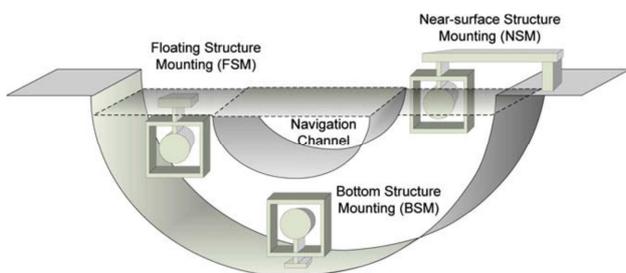


Figure 4. Turbine mounting options [17].

The position of BSM arrangement system is fixed near the seabed. This structure needs to pile on the seafloor. Or it can use gravity base structure principle. NSM is the system mounted at other structure that close to the surface water and coast side. FSM operates under some variable elevations because the structure is affected by tidal currents or wave. Stability of pontoon to muffle is affected by external force and dynamic force of turbine rotation which it become an important issue. It can effect overall performance of the system. Mooring systems is an important part to maintain the position and the stability of FSM system.

### 3.0 VERTICAL AXIS TURBINE

In recent years, many researchers are very interesting to develop vertical-axis turbine because it has many advantages, but also has some drawbacks. Khan et al. [17] tried to give illustration in Figure 5 about various arrangements under this type.

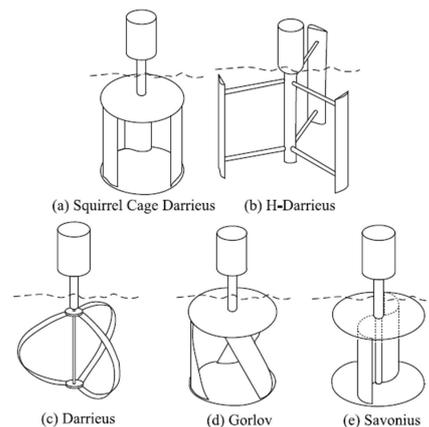


Figure 5. Vertical-axis turbine arrangements [17].

Darrieus turbines are most known in vertical type. Darrieus turbine arrangements are divided in two categories, they are straight blade (Squirrel Cage Darrieus and H-Darrieus) and curved blade (Darrieus). H-Darrieus have been proposed or demonstrated by Alternative Hydro Solution [44], New Energy [45], Blue Energy [46] and others. Gorlov turbine is an

innovation from modified Darrieus turbine for getting better performance [47, 48, 49]. Its blade shape is helical structure. Darrieus turbines and Gorlov turbine are lift type devices. Differ with Savonius turbine, it is a drag device.

### 3.1 Advantages

The vertical axis tidal current turbine possesses some advantages that promising to be developed are:

1. Simple design [17, 26]: Most of vertical-axis turbine blades are in straight arrangement, the design is more simple than horizontal axis type. Blades of horizontal-axis turbine have complex geometry modifications (such as taper, twist, winglet and others) that need delicate machining and manufacturing.
2. Inexpensive manufacture [26]: Its simple design gives effect on manufacturing process. It can be produced by simple machining. So the total system cost can be reduced. As an emerging technology, cost consideration is an important consideration to decide steadily switching dependency from fossil fuel to renewable energy.
3. Generator placement [17, 26, 25]: In marine environment especially for hydrokinetic applications, the equipments are exposed to water. As an electrical component, generator need to be sealed, so this is become one challenge. In horizontal-axis turbine, gear and generator must be placed in underwater. In contrast to vertical-axis turbine, generator can be coupled in one end of the shaft. So it can be placed on top and can reduce the cost in arranging water-sealed technology.
4. Simple installation [26]: Since generator, gear and other electrical components can be placed above water surface, it is able to use simple installation. Afterwards in operation phase, it eases the operator to repair or maintenance.
5. Flotation as augmentation equipment [17]: The pontoon can be used as flotation and also as augmentation equipment. Vertical-axis turbine has cylindrical shape that are possible to mount various curvilinear or rectilinear ducts. The channel also can be employed for floating and mooring purposes [50].
6. Any flow direction [26, 25, 51]: Tidal currents are not always coming from one direction. Tidal currents in narrow cross-section usually come from bi-direction, whether diurnal (24 hours) or semi-diurnal (12 hours) type. Vertical-axis turbine can respond any flow from any directions. So it does not need any yaw mechanism.
7. Skewed flow [17]: Tidal currents have variable velocity in each elevation. In upper position there are currents that generated by wind force then it decrease gradually. The skewed flow is also caused by boundary conditions (orography or bathymetry). Vertical-axis turbine still can generate power. Because it has radial arm with hydrofoil section and it behave some slight extent like Wells turbines that still contributing some power.
8. Turbulent flow [25]: Vertical-axis turbine also can be used in turbulent flow. Vertical-axis turbine, especially with helical blades, is reportedly more suitable for operation under turbulent condition [52]. So the kinetic energy still can be converted optimally.
9. Reduce blade tip losses [26]: Blade tip of horizontal-axis turbine normally generate a turbulence wake. It is known as tip losses. It needs modification such as winglet to reduce the tip losses. In opposite condition, that problem does not exist

in vertical-axis turbine.

10. Low noise emission [17, 26]: Since vertical-axis turbine can reduce tip losses, turbulence flow are reduced. It gives effect on creating less noise. Thus vertical type can mitigate the negative impact on marine life and their habitat.
11. Compactness [53]: On wider applications, tidal current turbines can be placed in arrays. Vertical-axis turbine pack is more efficient in arrays because it has a rectangular cross-section, different with horizontal axis type has circular cross-section.

### 3.2 Challenges

The challenges associate with vertical axis tidal current turbine that must be answered are:

1. Irregular current velocity: Both on all hydrokinetic turbine types, irregular current velocity is normal challenge. The current movements of seawater are dominantly driven by changing tides. Tides has predictable velocity according to tide time or ebb time. However, tidal currents velocity are irregular and fluctuating depending on location and specific time.
2. Low efficiency [17, 25]: Vertical-axis turbine has lower efficiency than horizontal axis type. Theoretically performance coefficient of vertical type can reach 64%, but in practically the efficiency is still under the horizontal type.
3. Low starting torque [17, 26, 25]: Generally, vertical type possesses poor starting performance. External mechanical or electrical starting mechanism can be applied. However, it can increase cost and design complexity. There is an innovation like variable pitch to be self-start component for answering this challenge [25].
4. Torque ripple [17, 26, 25]: In vertical type there are terms of upstream and downstream area classification. Tidal currents velocity reduce from upstream to downstream area after it passes turbine rotation. It will emerge the different fluid dynamic force on blades. Each blade experience two peaks load in both radial and tangential force per revolution approximately 180° apart. The variation of tangential force is best known as torque ripple.
5. Fatigue loading [17]: The variation of radial force can effect on shaft or bearing. The closest effect is friction on bearing and other effect is broken in shaft. It happened experimentally in towing tank [54]. Shaft can not resist fluctuation force with a big peak.
6. Vibration [26, 25]: The variation of radial force also can effect on the supporting structure and other equipments. It is known as vibration. Some components like generator is very sensitive on vibration. In other hand, if this vibration frequency coincides with natural frequency of the support structure, it can be destructive.
7. Low RPM: Hydrokinetic turbine operates at rate velocity 2-3 m/s and it can produce four times energy similar with a rate wind turbine [37]. Fluid density of water is approximately 1,000 kg/m<sup>3</sup> and density of wind is approximately 1.221 kg/m<sup>3</sup>. Wind turbines are designed to operate at rate wind velocity 11-13 m/s [55]. Instream Energy System [31] uses a vertical-axis turbine which operate at 3 m/s water velocity can be generated 30 RPM. It means that hydrokinetic turbine always has lower RPM than wind turbine. Generally, generator's rotation specification is in high RPM, so it must

apply increaser gear. Alternatively, it can choose low RPM generator or if there is not its specification in the market then have to design the generator by own self.

8. Cavitation [17, 26]: Cavitation is always to be challenge in hydrokinetic turbine. It can be defined as the formation of water bubble or voids when local pressure falls below the vapor pressure. Slowly it can damage turbine material. Rough blade surface will decrease the performance.
9. Ocean environment is harsh [54] and salty: Great tidal currents energy sources can be found in harsh environment. Until today, Ocean Engineering usually concern to choose location with environmental friendly. However this technology needs in contrast situation. Ocean is also salty environment. Corrosion is the most problem that will be faced in ocean environment.
10. Marine fouling: All technology that operate in marine environment can be attached by marine fouling. It can attack turbine blades. The surface of blades will be rough. It increase loads then finally decrease the performance. The maximum power coefficient will decrease approximately 19% (from 42% to 34%) compare to baseline clean blade [56].
11. Buoyancy: An upward force is exerted by fluid that opposes the weight of an immersed object. It is known as buoyancy, which is something that never predictive before and can be interfered the performance of the turbines. This force drive up the shaft and make the gear on shift position. It causes friction and even causes congestion the rotation.

#### 4.0 DISCUSSIONS

Ocean energy resources will contribute to the world's future renewable energy supply, especially tidal current power generation. Ocean energy development current status in Europe show that tidal energy lead in market maturity level [57]. OES Annual Report 2015 report about most of the countries that develop ocean energy are developed countries [58]. Even though some developing countries also have good resource of tidal current energy but most of them do not concern in ocean energy development. As an example, Lim et al [59] have done analytical assessments on tidal current potential in Malaysia, the total amount of electricity that can be generated is about 14.5 GWh/year. Moreover Indonesia has practical potential energy of tidal currents about 17.9 GW [27]. If it assumes that 8760 hour per annum and low capacity factor of around 14% (capacity factor value base on reference [60]), the total amount of electricity that can be generated is about 21,952 GWh/year. Indonesia tidal current energy potential is much bigger than Malaysia. Both developed and developing countries can collaborate and contribute for tidal current energy development for aiming sustainable renewable energy.

Vertical-axis turbine has some advantages that have been discussed in the previous section. The advantages are suitable for countries that want to start developing tidal current energy. They do not have production technology capability, ocean energy policy, good funds allocation for research, open sea testing facilities, towing tank for experimental study and others. However, researcher in that countries still can begin with analytical or numerical study to solve the challenges in vertical-axis turbine.

The main challenges that must be answered in vertical type are low efficiency, low starting torque and torque ripple. As an example, some numerical studies in vertical-axis turbine have been done by using Computational Fluid Dynamic software [61, 62, 63]. Those studies tried to learn performance characteristics of vertical-axis turbine and also tried to gift some modifications for getting better performance.

Tidal current resources can be found in nearshore and particularly constrictions area, such as islands, straits and passes. Tidal current have spesific velocity profile that is influenced by bathymetry (shape of the seabed), orography (shape of the land) and the roughness of these surfaces. Floating structure or FSM is a good rotor placement option for extracting tidal current energy. Tidal current velocity is optimally in that area because it is not disturbed by the boundary conditions. Furthermore vertical type has advantage that generator, gear and other electrical components can be placed on top. Therefore vertical-axis turbine is very suitable for floating structure.

#### 5.0 CONCLUSION

Hydrokinetic energy conversion system as ocean renewable energy resources is to be emerging technology that can resolve the problem of fossil energy. The worldwide theoretical power of tidal power has been estimated around 7,800 TWh/year [1]. It is very huge energy resources and very exciting to be used. Vertical-axis turbine possesses some advantages that are simple design and installation, cheaper in production, easier in operation because generator, gear and other electrical components can be placed on top and suitable for floating systems. Those are excess of it is in accordance with the conditions of marine environment and production technology capabilities that exist in some developing countries. The main challenges that must be answered and solved in vertical axis tidal current turbine are low efficiency, low starting torque and torque ripple. In consequence, study, research and development program are still needed until making it to be mature technology.

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