# Marine Hydrokinetic Energy Generation Systems and Their Performance Indicators

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## ABSTRACT

As an important clean and renewable energy, tidal energy is attracting more and more attention, and various plan and projects are being made worldwide to generate power. First, this paper discusses the current status of tidal power generation, and then describes Marine Hydrokinetic (MHK) energy turbines and related facilities. Then, the paper proposes performance indicators of the power generation systems in aspects of their power output estimate and reliability.

## INTRODUCTION

According to a recent survey, the global energy consumption in 2007 is 11103 million tons of oil equivalence, and this consumption consists of 35.6% oil, 23.8% natural gas, 28.6% coal, 5.6% nuclear power, and 6.4% hydroelectricity, with 88% of it coming from fossil fuels (IEA, 2007; Rourke et al., 2010). The heavy dependence on fossil energy now results in an unprecedented consequence that challenges the whole world; at the current rate of exploitation, this type of energy is expected to be exhausted in a near future. Even more, burning of fossil fuels produces $CO_2$ and has led to the greenhouse effect, which results in global warming and climate change (US NREL, 2005).

In recent years, more and more attention has been shifted to clean and renewable energy, and various plans and pilot projects have been developed to move away from using fossil fuels as the primary source of energy generation. Tidal energy is a clean and renewable energy, and it is able to provide a significant amount of energy. A study completed in 1999 by the Marine Oversight Committee of the British House of Commons concluded: “if 1/10 of 1% of the energy in the world’s oceans could be converted into electricity; it would supply the world energy demand five times over.”

At present about 5% of the UK's electricity comes from renewable energy resources. With a plan to produce 20% of its total energy from renewable resources by 2020, which corresponds to about 35% of its electricity demand, the UK is exploring to increase generation of renewable energy from tidal sources (DTI, 2003; Xia et al., 2010). The Korean government plans to increase investment on alternative energy sources in the country's energy spending from current 1.4 percent to 5 percent by 2011 (Lee and Yoo, 2009). New Jersey State has set goals to achieve 20% renewable energy generation by 2020 and considers tidal energy as an important part of it. It is estimated that if only 1% of the New Jersey shoreline is utilized for tidal energy production, it could contribute an estimated 500 MW or more power based on presently available technology during the next 2-3 years, while adding over $1 Billion to the New Jersey economy in the next decade (NJDOT 2010). The first tidal energy site in New Jersey received its Waterfront Development Permit from the NJ Department of Environmental Protection (NJDEP) on January 14, 2010.

Tidal energy consists of potential and kinetic components. Accordingly tidal power facilities are categorized into two types: tidal barrages and tidal current turbines, which use the potential and kinetic energy of the tides, respectively (Lemonis & Cutler, 2004). A tidal barrage is typically a dam, built across a bay or estuary that experiences a tidal range in excess of 5 m, and electricity generation from it employs the same principles as hydroelectric generation, except that tidal currents flow in both directions (IET, 2007). Tidal barrage is the main form in tidal energy generation at the early stage in its development. Currently, there are four such power plants in operation in the world. The four plants are La Rance, France, built in 1960's, Jangxia Creek, east China sea, constructed about the same time, Kislaya Guba power facility, Russia, also built in 1960, and Annapolistidal generation, Canada, finished in 1980's. Technology of electricity generation using tidal barrages has become mature and reliable. However, in consideration of cost and environmental impact, it is now a trend to utilize Marine Hydrokinetic (MHK) energy and tidal current turbines in tidal power generation. Currently the technology of MHK energy power generation is still in its infancy, and various problems are involved and need investigation. Reviews for tidal power generation can be found in Khan et al., (2009) and Rourke et al. (2010).

This paper deals with MHK energy generation and facilities and discusses related performance indicators.

## MHK ENERGY, TURBINES, AND SUPPOERTING STRUCTURES

Marine Hydrokinetic (MHK) energy comes various motions of coastal ocean waters. MHK energy of a current can be evaluated using the per square meter transient kinetic energy flux *F* as follows (e.g., Carballo, 2009):

$$F = \frac{1}{2}\rho V^3 \qquad (1)$$

where $\rho$ is the density of water and $V$ is the transient depth-averaged velocity. With the seawater density of 1030 kg/m$^3$, it is known from this formula that the kinetic energy flux is about 515 W/m$^2$ at $V$=1 m/s and 4120W/m$^2$ at $V$=2 m/s. This indicates that water current contains a large amount of energy that increases rapidly with its velocity.

In power generation using MHK energy, the energy flux will be transformed into electricity by current power generation systems (Fig. 1). A simple current power generation system consists of four parts: 1) a turbine, 2) a gear box, 3) an electricity generator, and 4) a supporting system. Parts 1), 2), and 3) of the system are mounted to the supporting structure 4). Flowing water turns the turbine by propelling its blades, the gear box transfers the rotation of the turbine into motion of the generator, and the generator transforms the energy of its mechanical motion into electricity, which is transmitted to land through cables.

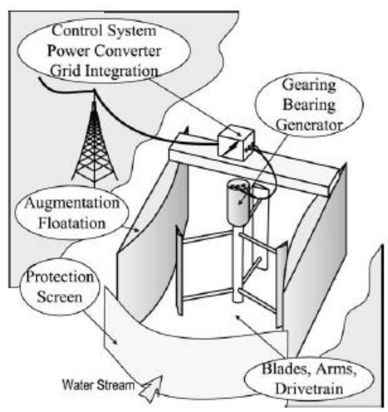


**Figure 1. Schematic representation of power generation using MHK energy (from Khan et al., 2009).**

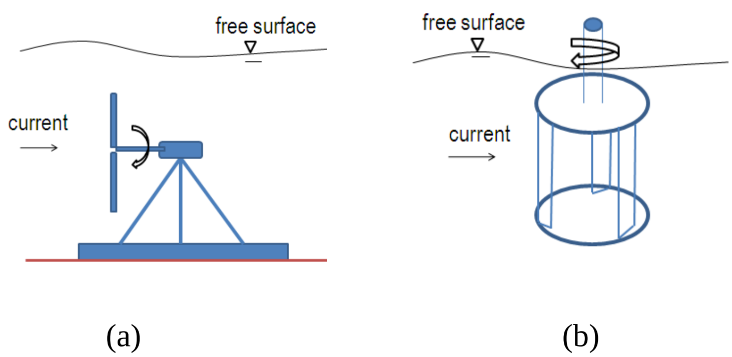


**Figure 2. Categories of MHK energy turbines. a) Horizontal axis turbines. b) Vertical axis turbines.**

Turbines using MHK energy fall primarily into two categories: vertical and horizontal axis turbines (Khan et al., 2009), as illustrated in Fig. 2. Horizontal axis turbines are common in tidal energy converters and are very similar to modern day

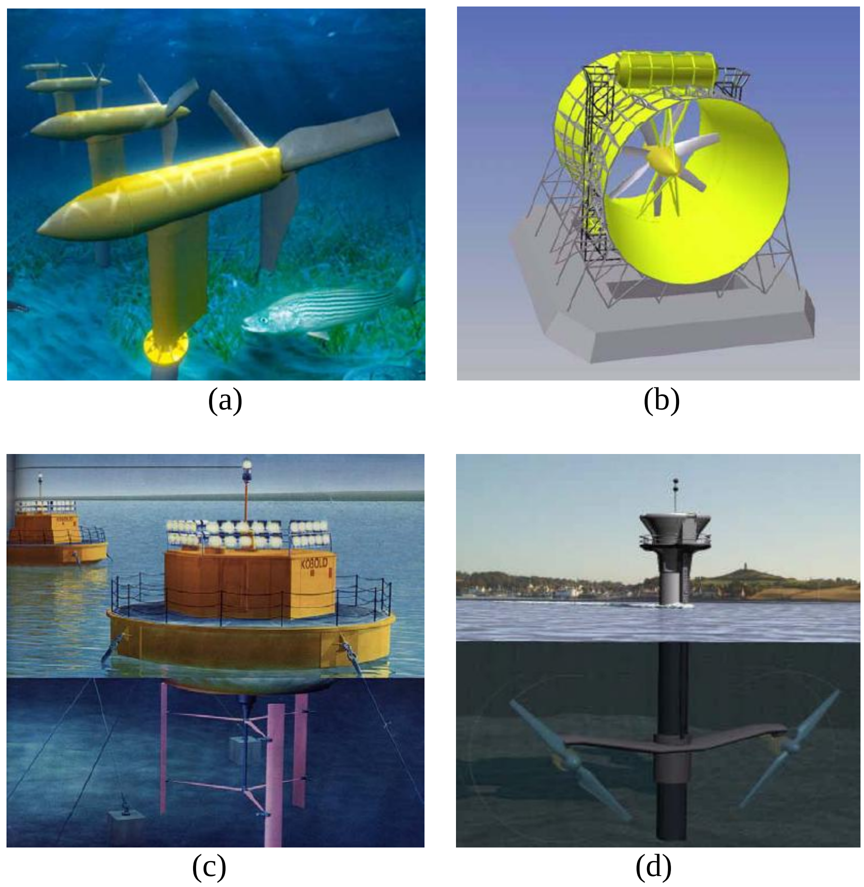


**Figure 3. Examples of tidal current turbines (from Bedard, 2005; Rourke et al., 2010). (a) Free flow turbine. (b) Lunar energy tidal turbine. (c) Kobold turbine. (d) Marine current turbine.**

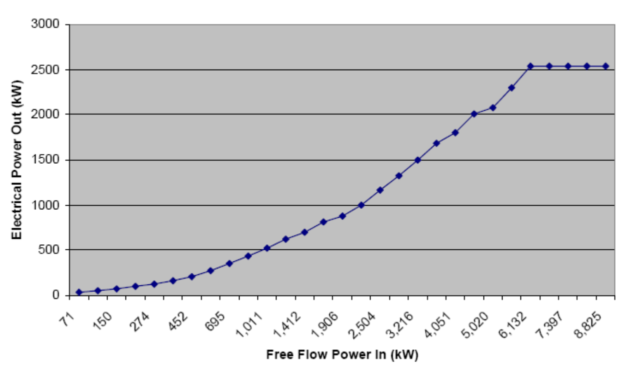


**Figure 4. Power curve of Marine current turbine (from Bedard, 2005).**

wind turbines from concept and design point of view. MHK turbines can be either mounted on the structures at seabed or floating structures floating in water. The floating structures are usually moored to the seafloor using chains or wires. Fig. 3 presents examples of several actually designed MHK turbines. Various investigations have been made to characterize the efficiency of the turbines (e.g., Bedard, 2005), and Fig. 4 presents the efficiency for one of such MHK energy turbines.

From Eq. (1) it is known that kinetic energy flux from a fluid flow is proportional to the cube of the stream velocity of the flow. Therefore, in order to increase the available MHK energy flux, it is crucial to obtain a large flow velocity. For this purpose, augmentation channels are proposed for MHK turbines (Setoguchi et al., 2004; Ponta and Jacovkis 2008). Fig. 5 presents an augmentation channel supporting a floating water current turbine. A simple channel may consist of a single nozzle or cylinder or straight path. In a hybrid design, all the three options may be incorporated in one unit. A survey shows that around one-third of the horizontal axis turbines are considered for such arrangements, and almost half of vertical turbines are planned with some form of augmentation (Khan et al., 2009).

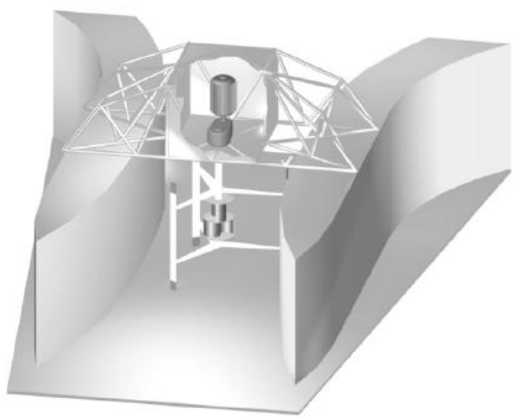

**Figure 5. A designed and tested argumentation channel for a floating MHK turbine (from Ponta and Jacovkis, 2008).**

## PERFORMANCE INDICTORS

It requires a significant amount of historical data and effort to develop a realistic velocity process for a geographic site. Consider a site with an annual tide current velocity history as shown in Fig. 6. Frequently, for a tide power generation device, there is a cut in and cut out velocity. The device stops working at a current velocity lower than the cut in velocity or higher than the cut out velocity. The output power *P* of such device can be expressed as follows:

$$P = \begin{cases} \frac{\eta}{8}\pi\rho V^3 D^2, & V_{ci} \le |V| \le V_{co} \\ 0, & otherwise, \end{cases} \quad (2)$$

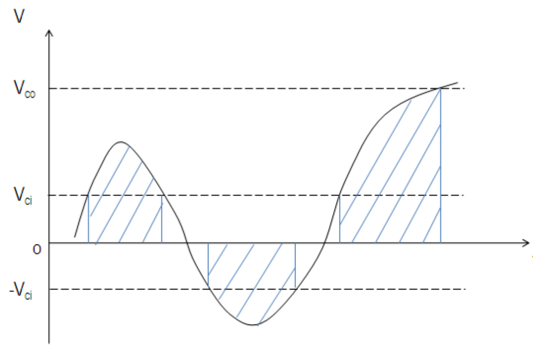


**Figure 6. Current velocity history. The shadow area indicates MHK energy available for a turbine to generate power.**

where $D$ is the diameter of the blades $\eta$ is the efficiency coefficient of the turbine, and $V_{ci}$ and $V_{co}$ are respectively the cut in and cut out velocity. The annual average output of the device $\overline{P}$ reads as

$$\overline{P} = \frac{\eta\pi\rho D^2}{2T}\int_0^T |\hat{V}|^3\, dt, \quad (3a)$$

$$\hat{V} = \begin{cases} V, & V_{ci} \le |V| \le V_{co} \\ 0, & otherwise, \end{cases} \quad (3b)$$

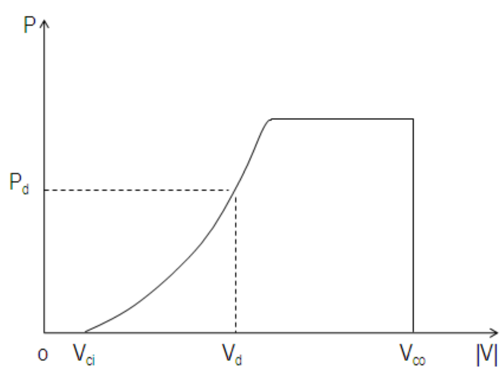


**Figure 7. Power curve of MHK energy generation system. $P_d$ is the designed minimum power output of the system, and $V_d$ is the corresponding current velocity.**

where $T$ is one year duration or $3.1536 \times 10^7$ s. In view of the cut in and cut out velocity and other specifications, the power curve of a MHK energy generation system can be modeled as that shown in Fig. 7 (Bedard, 2005; Karki et al, 2006).

Suppose the velocity of a selected site at a time follows a probability distribution function $f$ as shown in Fig. 8. Unlike wind power generation (Karki et al., 2006), two directions rather than one direction of flow are considered. At a given time at this site, the probability that a current is available for a MHK energy generation system to produce designed power output $P_d$ will be

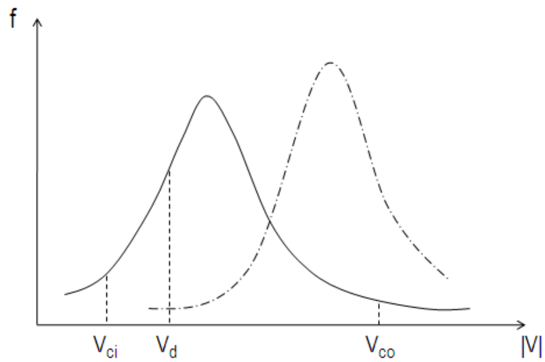


**Figure 8. Probability distribution function of current velocity.**

$$p_d = p(V_d \leq |V| \leq V_{co}) = \int_{V_{ci}}^{V_d} fd\,|V|, \tag{4}$$

and the probability that the system cannot generate the designed power output will be

$$p_{nd} = p(|V| < V_d \cup |V| > V_{co}) = 1 - p(V_d \leq |V| \leq V_{co}). \tag{5}$$

Let the probability that the turbine, the gear box, the generator, and the supporting structure of a MHK energy generation system be at working states be $p_t$, $p_b$, $p_g$, and $p_s$, respectively. Since all of these components are subject to impact of water and air flows, the probability if they are at working states will be related to the categories of hurricane classes. Hurricanes are classified into five categories as shown in Table 1, and the observations of damages on structures due to them have been found (ORACLE ThinkQuest, 2011).

Let index $i$ denote the categories of hurricane 0, 1, 2, 3, 4, and 5, and the probability of occurrence of them are $p_h^{\ i}$. Assume the probability that the turbine, gear box, the generator, and the supporting system are working under the condition of hurricane $p_h^i$ is respectively $p_t^i$, $p_b^i$, $p_g^i$, and $p_s^i$. Then, according to the theorem of total probability, the probability for the turbine at working condition is (Ang and Tang, 2007)

**Table 1 Hurricane category and its wind speed, storm surge height, and air pressure (from ORACLE ThinkQuest, 2011).**

| Category | Wind Speed | Surge Height | Central Pressure |
|---|---|---|---|
| 0 – No hurricanes | <74 mph | <4 feet | > 28.94 in |
| 1 - Minimal | 74 - 95 mph | 4- 5 feet | >28.94 in |
| 2 - Moderate | 96 - 110 mph | 6 - 8 feet | 28.50 - 28.91 in |
| 3 - Extensive | 111 - 130 mph | 9 - 12 feet | 27.91 - 28.47 in |
| 4 - Extreme | 131 - 155 mph | 13 - 18 feet | 27.17 - 27.88 in |
| 5 - Catastrophic | >155 mph | >18 feet | < 27.17 in |

$$p_t = \sum_{i=0}^{5} p_t^i \cdot p_h^i , \quad p_b = \sum_{i=0}^{5} p_b^i \cdot p_h^i , \quad p_g = \sum_{i=0}^{5} p_g^i \cdot p_h^i , \quad p_s = \sum_{i=0}^{5} p_s^i \cdot p_h^i . \qquad (6)$$

Then, the probability for a single MHK energy generation system to output designed power at the given time will be

$$p_o = p(P > P_d) = p_d \cdot p_t \cdot p_b \cdot p_g \cdot p_s . \qquad (7)$$

In Eqs. (6) and (7), the probability $p_d$ , $p_h^i$ , $p_t^i$ , $p_b^i$ , $p_g^i$ , and $p_s^i$ will be evaluated on the basis of information on manufacture, constructions, weather and current conditions at the sites.

Suppose that there are *N* MHK energy generation devices at a tide site and each of them is independent of each other, then the number of the devices that are producing the minimum required power output follows the binomial distribution (Ang and Tang, 2007). The probability of at least *M* ($M \leq N$) of them work at a given time is

$$p_N = \sum_{n=M}^{N} \binom{N}{n} p_o{}^n (1 - p_o)^{N-n} . \qquad (8)$$

Eqs. (2) and (3) are performance indictors on power output of MHK energy generation systems, and Eqs. (7) and (8) are those on reliability of them.

## CONCLUDING REMARKS

Tidal energy is now becoming a significant energy source for our society, and power generation using MHK energy has become a trend in its research and development. Although many technologies in hydro and wind power generation are potentially available for tidal power generation, many new problems are involved and investigations on new technologies are necessary. For instance, a crucial issue will be the estimate of reliability of tidal power systems including their individual components under conditions of normal tides as well as hurricanes at different categories, that is, the probability that involves in Eq. (7). How to make a robust electricity generators and circuits immersed in water? How to construct supporting system that can survive huge repeated hydrodynamic impact including that in thunderstorms and last long time? In addition, the impact of tidal energy generation on environments and ecological systems will be another crucial issue in its commercialization.

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