MECHANICAL MODELLING OF A MODULATED SINGLE POOL TIDAL ENERGY SYSTEM

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ABSTRACT

Lack of fossil resources and along with concerns about human health are the two main incentives for utilization and usage of renewable energies. Tidal energy is one of the most important forms of renewables which carry the electricity production capacity within its height differences and current flow. In this paper, we developed a time-dependent mathematical model for electrical energy generation from a single-pool tidal system. Using current model with available tidal data in port of Shahpur, Iran, extracted energy from this system can be calculated. Model results have shown that system has the capacity of producing 40.6 Megawatts electricity from tidal energy in this area. This study has show that there is a desirable potential for extracting renewable energy from tidal power within the south coast of Iran.


Green power describes electricity produced from renewables sources that are less harmful to the environment than fossil fuels. So energy produced from solar, wind power, geothermal, biomass, and small hydroelectric plants is considered green power. Renewable energy is an unending source of energy that quickly replenishes itself. Renewable energy does not cause pollution or release toxic substances into the atmosphere; of course, hydroelectric dams cause damage to flora and land area. Some renewable energy systems have environmental problems (Renewable Energy Focus Handbook, 2009). It is obvious that these problems are less compared to fossil fuels.

Hydro power or water power is considered as one of the most important renewables. High density of water which is almost 800 times larger than that of air causes the small velocity streams to produce significant amount of energy. Tidal power is a subcategory of water power. Tides can be utilized as energy sources through the currents they cause or through the associated variations in ocean level. The most effective way of taking advantage of these vertical water displacements is through impoundment, and this is the only approach being considered seriously. Average tidal fluctuations in the open sea are small; however, local resonances can magnify the tidal effect considerably (Da Rosa, 2009). Tidal power can be classified into three main types (Zobaa and Bansal, 2011):

- Tidal stream systems
- Barrages
- Tidal lagoons

Tidal stream systems make use of the kinetic energy of moving water to power turbines, in a similar way to windmills that use moving air. This method is gaining in popularity because of the lower cost and lower ecological impact compared to barrages.

Barrages make use of the potential energy in the difference in height (or head) between high and low tides. Barrages are essentially dams across the full width of a tidal estuary, and suffer from very high civil infrastructure costs, a worldwide shortage of viable sites, and environmental issues.

Tidal lagoons, are similar to barrages, but can be constructed as self-contained structures, not fully across an estuary, and are claimed to incur much lower cost and impact overall. Furthermore, they can be configured to generate continuously which is not the case with barrages.

Figure 1. Power Generation Cycle Using The Sea Level Difference In A Tidal Barrage System
(difference between mean high and low tides) of 5 m is required for plants using conventional hydroelectric equipment. More recently, low-head hydroelectric power equipment has proved adaptable to tidal power and new systems for 2-m ranges have been proposed (Goswami and Kreith, 2008). The mechanism of such systems is depicted in figure (1). The system is producing power between stages 2 and 3 as well as stages 4 and 1. Figure (1) shows a type of single pool tidal systems called single-pool two-way operation system which takes advantage of a bi-directional turbine; electricity can be generated both when the water flows into the pool at flood and when it flows out of the pool at ebb. This method has been successfully employed in the Rance Tidal Power Station (Zabihian and Fung, 2011; Ben Elghaliet al., 2007; en.wikipedia.org/wiki/Rance_Tidal_Power_Station (accessed 2014/26/01))

MODELLING OF BARRAGE SYSTEM

As figure (2) illustrates, it is assumed that at any instant of the time, the water level in the pool to be $y_b$ and the water level in the ocean or the sea to be $y_o$. The difference between these levels is denoted by $h$ as

$$ h = y_o - y_b $$  \hspace{1cm} (1)

and the differential of work done $\delta W$ due to the traveling of mass $dm$ from the pool to the ocean is therefore can be calculated as

$$ \delta W = g \cdot dm \cdot h = g \cdot dm \cdot (y_o - y_b) \hspace{1cm} (2) $$

where

$$ dm = \rho \cdot dy_b \cdot A \hspace{1cm} (3) $$

In equation (3), $A$ is the area of the pool and $\rho$ is the density of the sea water (usually considered 1025 $kg/m^3$). According to figure (4), the simplified model can be developed which is based on the time-dependent functions of water level in the pool and ocean. In other words,

$$ y_o = f(t) \hspace{1cm} (4) $$
$$ y_b = g(t) \hspace{1cm} (5) $$

where $f$ and $g$ are the functions of time $t$. Introducing equations (3), (4) and (5) into equation (2) yields

$$ \delta W = g \rho A [f(t) - g(t)] dA(t) \hspace{1cm} (6) $$

Thus, the total energy delivered to the turbine in ideal situation can be calculated using equation (7) as follow.

$$ W = \int_{t_1}^{t_2} g \rho A [f(t) - g(t)] dA(t) \hspace{1cm} (7a) $$

Based on figure (3), the process of power generation requires a minimum head so the level difference should be more than a specific value to allow the turbine gates to be opened. At the end of the cycle, the turbine gates will be closed, but the bypass gates remain open until the pool is filled or emptied. Therefore, the interval of integration is calculated from $t_1$ to $t_2$. We can estimate the sea water level $f(t)$ as a sinusoidal function with good approximation as

$$ f(t) = A \sin \left( \frac{2\pi}{T} t \right) \hspace{1cm} (8) $$
Figure 3. Water level variation profile in the ocean and the pool as a function of time

where is the semi diurnal tidal period equals to 12 hours and 25 minutes (12.416 hours) and according to the definition the tidal range is twice the sinusoidal amplitude, so the equation (8) can be simplified into equation (9).

\[ y(t) = A \sin(\omega t + \phi) \]

However the equation (9) is general and in this study, the available data in the region is directly used to achieve . Approximation of is difficult where it can be expressed as a linear function of time, a function of given a constant flow resistance or other functions determined from operational data. (10)

and the equation (10) can be rewritten as the following.

\[ y(t) = A \sin(\omega t + \phi) + B \]

Substitution of equations (8) and (10) into (7), we obtain

\[ y(t) = A \sin(\omega t + \phi) + B \]

or

\[ y(t) = A \sin(\omega t + \phi) + B \]

Which is calculated analytically and finally it is simplified to equation (13).

Figure 4. Variations of sea level in Port of Shahpour during August 2013 [8]
\[ W = \rho g AR^2 \left[ -\frac{T}{4a} \cos \left( \frac{2\pi}{T} t_2 \right) + \frac{T}{4a} \cos \left( \frac{2\pi}{T} t_1 \right) - \frac{(t_2-t_1)^2}{2a^2} \right] \]  

(13)

The variable \( T_0 = t_2 - t_1 \) is the generation period. Generated power per unit of the pool area \( P (J/h.m^2) \) is then achieved using equation (14).

\[ P = \frac{\rho g r^2 T}{4a t g} \left[ \cos \left( \frac{2\pi}{T} t_1 \right) - \cos \left( \frac{2\pi}{T} t_2 \right) - \frac{2 T g}{a T} \right] \]  

(14)

Equation (14) is the final model formula used for estimation of tidal output power.

**TIDAL DATA IN THE PORT OF SHAHPOUR**

According to the one-month period of Iran National Hydrography Centre [8], the values of \( T \) and \( R \) in equation (13) can be obtained. Glancing in the available data from different ports, it is simply concluded that the Port of Shahpour has greater tidal range compared to other ports which is sometimes twice the other places. Therefore, in this study, the model is conducted in this port during August 2013 and the graph of the first week is illustrated in figure (4). Because the variations are of significance, to achieve a more exact result, the period is subdivided into four weeks and the characteristic values are calculated for each section. We can use equation (15) to find the period \( T \).

\[ T = \frac{7 \times 24}{n} \]  

(15)

Where \( n \) is the number of troughs or crests of the sinusoidal function and the numerator is the total hours per week. For example, total crests for the first week is 13.75 so the period is 12.218 which is consistent with the value of \( T \) in equation (9). Similarly, the values of \( T \) and \( R \) are calculated and shown in table (1).

Using equation (14), the average power in August \( \bar{P} (W/m^2) \) is given with

\[ \bar{P} = \frac{\sum_{i=1}^{4} P_i t_i}{3600 \sum_{i=1}^{4} T_i} \]  

(16)

where \( P_i \) is the power for each week with its period and height and is shown in figure (5).

**MODEL RESULTS AND CONCLUSION**

Time value of \( t_1 \) in which the gates are closed in the first period is given to be 1 hour and the value of \( t_2 \) is assumed to be 5 hours (www.iranhydrography.org/default.asp (accessed 2013/05/09). Weekly power and the monthly average power is illustrated in figures (5) and (6), respectively. For different values of time constant \( a \). The time constant is unique for each pool design. Considering the pool area to be 170 km\(^2\) which is the available area in that region (Mahshahr) [5], ideal average power \( \bar{P}_{\text{total ideal}} \) for \( a = 8 \) hours can be obtained.

\[ \bar{P}_{\text{total ideal}} = 170 \times 10^6 \times 0.4048 = 68.8 MW \]  

(17)

The efficiency of tidal turbines are similar to that of wind turbines which follows the Betz’s limit (ElWakil, 1988). Therefore the average power will be

\[ P_{\text{total}} = 0.59 \times \bar{P}_{\text{total ideal}} = 40.6 MW \]  

(18)

Two newly founded tidal power plants are constructed in the United Kingdom and the South Korea between 2008 and 2009 with capacity of 1.2 MW and 1.5 MW, respectively (Twidell and Weir, 2006). Existence of such power plants in other countries remind it that according to the Iran’s vast potentials, not only it should be paid more attention to the renewable energies in the country, but also it is necessary to provide opportunities for the private sponsors to enter the arena so that these endless gifted resources can be used in the most efficient way.

**Table1. weekly tidal range and period for August 2013**

<table>
<thead>
<tr>
<th>week</th>
<th>tidal range (m)</th>
<th>period (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>first</td>
<td>2.25</td>
<td>12.218</td>
</tr>
<tr>
<td>second</td>
<td>2.75</td>
<td>12.679</td>
</tr>
<tr>
<td>third</td>
<td>4.00</td>
<td>12.330</td>
</tr>
<tr>
<td>forth</td>
<td>3.00</td>
<td>12.444</td>
</tr>
</tbody>
</table>

**Table2. Variations of power per unit of area for different weeks**

<table>
<thead>
<tr>
<th>week</th>
<th>average</th>
<th>0.5354</th>
<th>0.5130</th>
<th>0.5130</th>
<th>0.5354</th>
<th>0.4084</th>
<th>0.3300</th>
<th>0.2768</th>
<th>0.2383</th>
<th>0.2093</th>
</tr>
</thead>
</table>
Figure 5. Variations of power per unit of area versus time constant (a) for different weeks

Figure 6. Average monthly power versus time constant (a)

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