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Green Power Generation through Modulated Single-Pool Tidal Energy System

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Abstract: Renewable energy systems have much lower environmental impact than conventional energy technologies. 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, a time-dependent mathematical model for electrical energy generation from a single-pool tidal system is developed. Using current model with available tidal data, the extracted energy from this system can be calculated. Model results have shown that such system has the capacity of producing 40.6 Megawatts electricity from tidal energy for a specific area.

Keywords: Renewable Energy, Tidal Energy, Single Modulated Tidal System, Green Power Technology.

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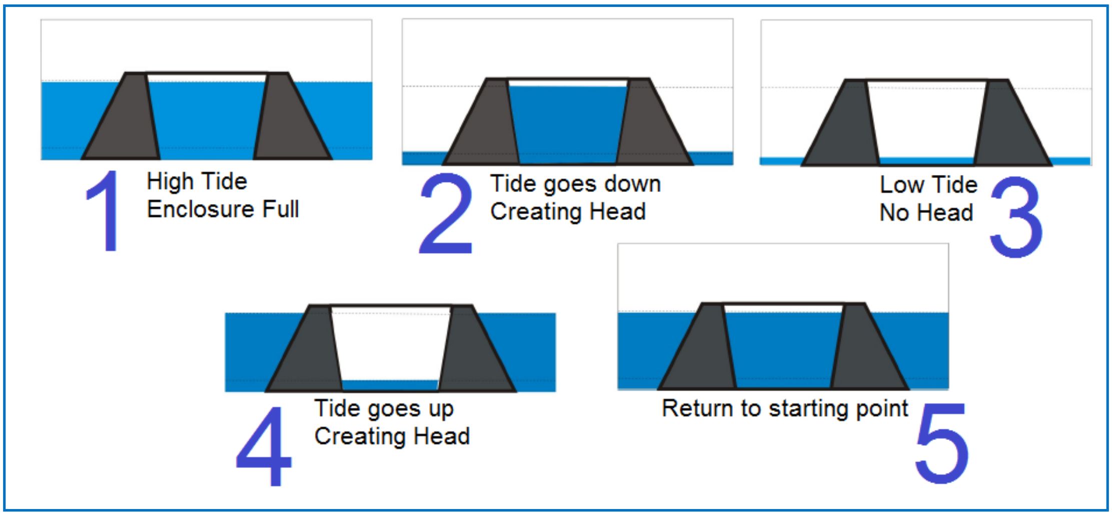
1. Introduction

Green power describes electricity produced from renewable 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 [1]. 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 [2,3,4]. 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 [5]. Tidal power can be classified into three main types [6]: tidal stream systems, tidal barrages and 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.

The second and the third method utilizes the potential energy of sea level differences. A minimum tidal range (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 [7]. 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 [8,9,10].

Figure 1. Power generation cycle using the sea level difference in a tidal barrage system.



2. 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

$$h = y_o - y_b \tag{1}$$

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

$$\delta W = g.dm.h = g.dm.(y_o - y_b) \tag{2}$$

where

$$dm = \rho.dy_b.A \tag{3}$$

In equation (3), A is the area of the pool and ρ 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,

$$y_o = f(t) \tag{4}$$

$$y_b = g(t) \tag{5}$$

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

$$\delta W = g\rho A[f(t) - g(t)]dg(t) \tag{6}$$

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

$$W = \int_{t_1}^{t_2} g\rho A[f(t) - g(t)]dg(t) \tag{7a}$$

Figure 2. Operation mechanism of a tidal barrage system and the model parameters

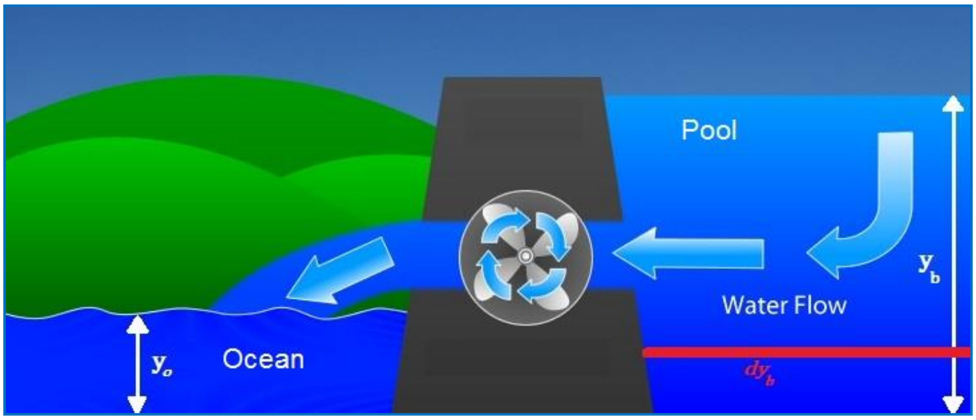
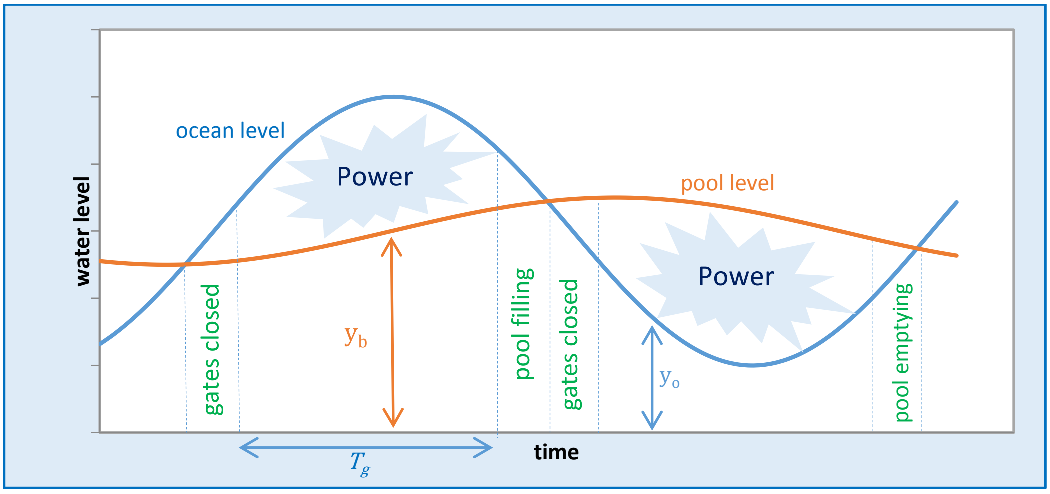


Figure 3. Water level variation profile in the ocean and the pool as a function of time



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

$$f(t) = A\,sin\left(\frac{2\pi}{T}t\right) \tag{8}$$

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

$$f(t) = \frac{R}{2}\sin\left(\frac{\pi t}{6.2083}\right) \tag{9}$$

However the equation (9) is general and in this study, the available data in the region is directly used to achieve T. Approximation of y_b is difficult where it can be expressed as a linear function of time, a function of h given a constant flow resistance or other functions determined from operational data. Here, the linear time-dependent function is chosen. It is assumed that the pool is empty at instant t_1 (i.e. it has the same level as the ebb) so the level variations in the pool take the following form

$$g(t) = b(t - t_1) \tag{10}$$

Assuming that the pool is filled in a hours, in the ideal case the pool level traverse the tidal range R, in fact, the tidal range will never traverse and it is clear from figure (3). Thus, from equation (10) we obtain

$$g(full) = R + g(empty) = R + 0 = b.a \tag{11}$$

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

$$g(t) = b(t - t_1) \tag{12}$$

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

$$W = \rho g A \int_{t_1}^{t_2} \left[\frac{R}{2} sin\left(\frac{2\pi}{T}t\right) - \frac{R}{a}(t - t_1)\right] d[\frac{R}{a}(t - t_1)] \tag{7b}$$

or

$$W = \rho g A R^2 \int_{t_1}^{t_2} \left[\frac{1}{2a}\sin\left(\frac{2\pi}{T}t\right) - \frac{t - t_1}{a^2}\right] dt \tag{7c}$$

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

$$W = \rho g A \int_{t_1}^{t_2} \left[\frac{R}{2} sin\left(\frac{2\pi}{T}t\right) - \frac{R}{a}(t - t_1)\right] d[\frac{R}{a}(t - t_1)] \tag{13}$$

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

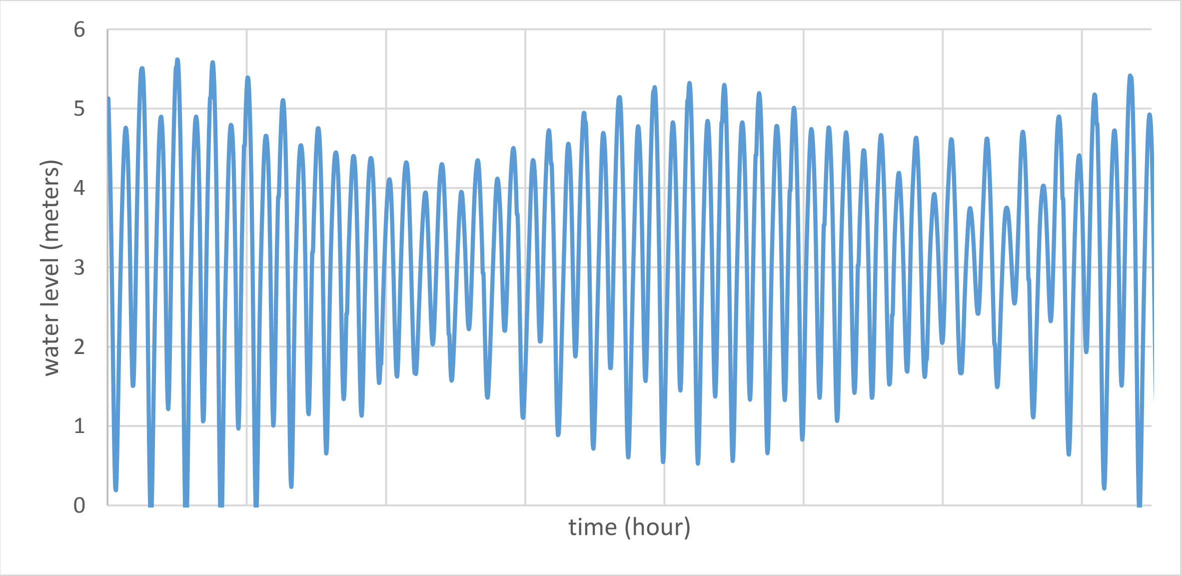
$$P = \frac{\rho g R^2 T}{4aT_g}\left[cos\left(\frac{2\pi}{T}t_1\right) - cos\left(\frac{2\pi}{T}t_2\right) - \frac{2}{a}\frac{T_g}{T}\right] \tag{14}$$

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

3. Results and Discussion

For the water level profile illustrated in figure (4), the values of T and R in equation (13) can be obtained. 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.

Figure 4. Variations of sea level versus time for one month



$$T = \frac{7 \times 24}{n} \tag{15}$$

Where n is the number of trughs or crests of the sinsoidal function and the numinator is the total hours per week. For example, total crests for the first week is 13.75 so the period is $12.218s$ 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

$$\bar{P} = \frac{\sum_{i=1}^{4} P_i\, T_i}{3600 \sum_{i=1}^{4} T_i} \tag{16}$$

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

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. 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^2which is the available area in that region, the ideal average power $\bar{P}_{total,ideal}$ for $a = 8$ hours can be obtained.

$$\bar{P}_{total,ideal} = 170 \times 10^6 \times 0.4048 = 68.8MW \tag{17}$$

Table 1. weekly tidal range and period

week	tidal range (m)	period (h)
first	2.25	12.218
second	2.75	12.679
third	4.00	12.330
forth	3.00	12.444

Figure 5. Variations of power per unit of area versus time constant (a) for different weeks

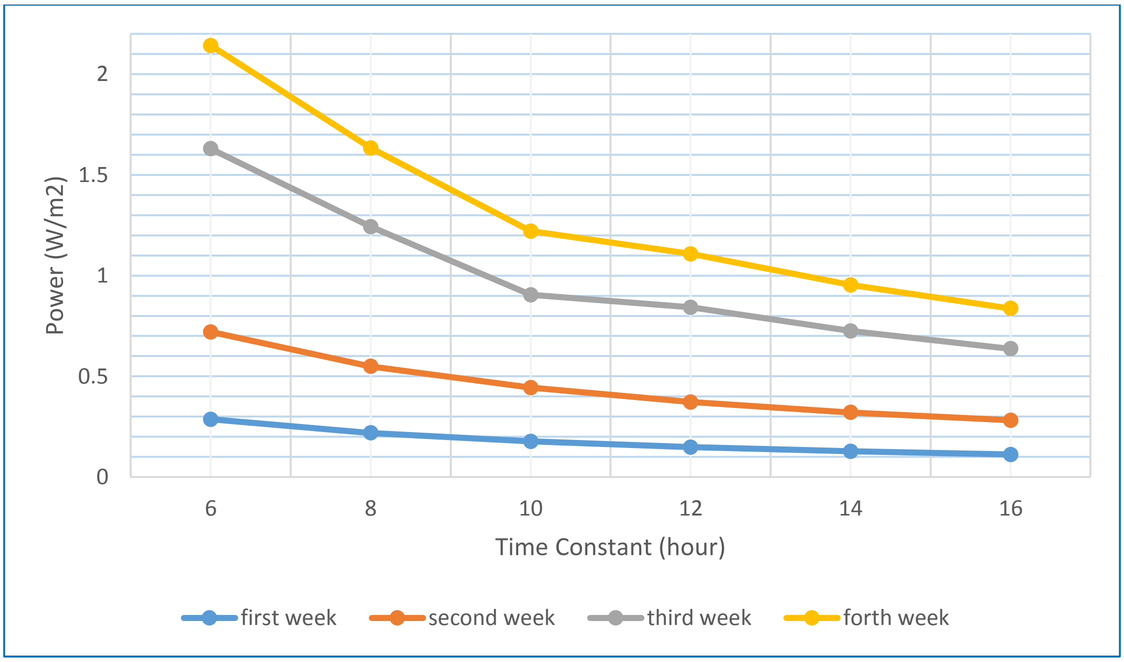
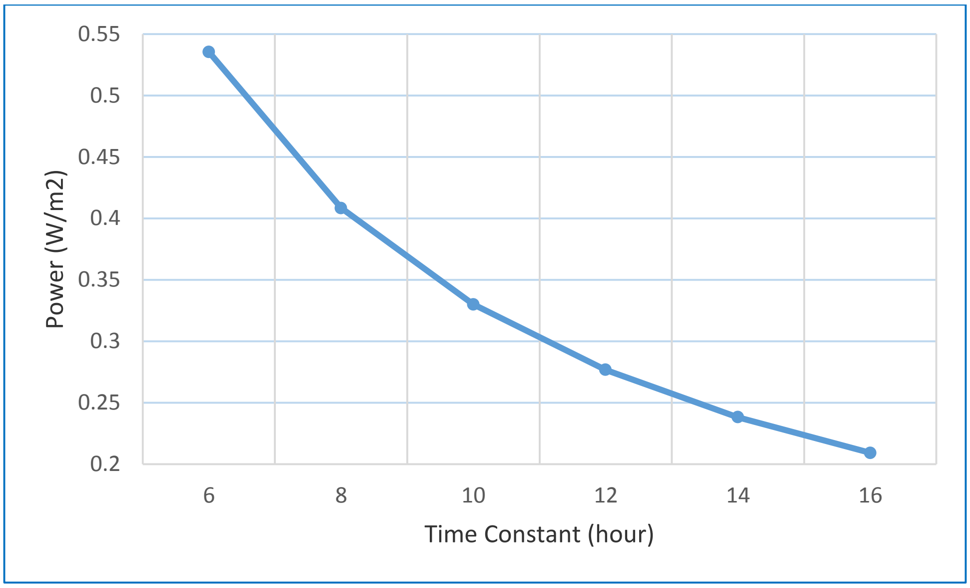


Figure 6. Average monthly power versus time constant (a)



The efficiency of tidal turbines are similar to that of wind turbines which follows the Betz's limit [5]. Therefore the average power will be

$$P_{total} = 0.59 \times P_{total,ideal} = 40.6MW \qquad (18)$$

4. Conclusions

In this study, a simple model is developed to calculate the energy extracted from a modulated tidal energy system. The time constant for barrage charging and discharging is the most important parameter in the formula which depends to the system design. It is obtained that for a pool with 170 km^2 area and a system with time constant of 8 hours, the maximum extracted power is estimated to be near 40 MW.

Conflict of Interest

The authors declare no conflict of interest.

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