Asian Journal of
Scientific Research

Improvement in the Performance of a Tidal Power Plant Incorporating Ebbing, Positive and Negative Pumping

Subhav Jain, Suvansh Bansal, Yash Khanna and Samsher

Department of Mechanical Engineering, Delhi Technological University, (Formerly Delhi College of Engineering), Bawana Road, 110042, Delhi, India

Corresponding Author: Subhav Jain, Department of Mechanical Engineering, Delhi Technological University, (Formerly Delhi College of Engineering), Bawana Road, 110042, Delhi, India

ABSTRACT

Considering the ever decreasing non-renewable energy resources, it has now become imperative to not only make use of more renewable energy sources but also to realise their maximum potential. After studying the working and performance of a few operational tidal power plants, this study aims at improving the power output of one such plant situated on Lake Sihwa in the Yellow Sea in South Korea. For achieving better results the operations must be carried out at optimum operating conditions. The present operation utilizes Kaplan Turbine based flooding operations only. Some improvements have been identified to increase the power output of the above discussed plant. There is potential for these operations to be extended, in particular to make greater use of pumping as well as ebbing. It has been found out that the power output increases considerably and hence can help in meeting the increasing energy demands of the nearby areas of the plant. In this paper the power output was increased by 6.9 and 29.6% through two different process combinations, respectively. Hence a net increment of 21.25% in power output was evaluated, incorporating pumping only.

Key words: Renewable energy, tidal power, two way generation, operating modes

INTRODUCTION

The present world wants to generate more and more energy for its populace and is striving to harness the resources to the maximum potential. The inevitable decline in the reservoir of fossil fuels combined with the ever increasing threat of global warming calls for an even more concerted effort to tap more of the renewable energy sources. Presently the fossil fuels still enjoy a lion's share of the global energy consumption and the share of nuclear, hydro and other renewable energy sources together is very less. High initial start-up cost for all renewable sources is an inhibiting factor. The generation cost per unit power should be lowered so as to make the venture profitable. The cost can be reduced by converting huge potential of renewable energy into sustainable quantity of power.

If even 0.1% of the ocean energy could be converted into electricity it would satisfy the present world demand for energy more than five times over (Muzathik *et al.*, 2011). Hence, to harness the energy possessed by water in the form of tidal waves, a sufficiently large basin area also ensures high volumes of water available to drive the turbines. Presently, tidal power occupies a very small fraction (2%) of the renewable energy spectrum employed for power generation (Expert Group on Renewable Energy, 2005). The sites of tidal power plants do not generate noxious effluents and

discharge which afflict the environment. Moreover they are in keeping with the natural surroundings and have proved to be successful as modes of transportation apart from boosting local tourism. When compared with the hydroelectric plants that employ dams there is negligible flooding of land in the vicinity in the case of construction of a tidal barrage and thus attracts less criticism. Tidal power scores over nuclear energy also as it is void of harmful radiation products which accompany a nuclear reaction.

This study aims to bring forth the shortcomings that prevail in present tidal power projects with respect to the implementation of certain techniques and their efficient utilisation. This in turn plays a significant role in mitigating the dangerous impact of fossil fuels.

The most successful full scale tidal power station i.e., the La Rance plant pioneered the technique of generating electricity during high and low tides. The La Rance plant situated on the river Rance in France boasts of 10 turbines with a combined installed capacity of 240 MW, generating 540 GWh year^{-1} of electricity. The basin area feeding the plant is nearly 22 km^2 and the average tidal range is 8.5 m which can attain a peak value of 13.5 m during the spring tides. The power station has been operational since 1967 and is supplying electricity to more than 300,000 homes. The modes of operations and other processes involved are explained as in Fig. 1.

Ebb generation: Sluice gates allow the basin to be filled in until the high tide and positive pumping is employed to create sufficient head across the barrage on closing the gates. Then the
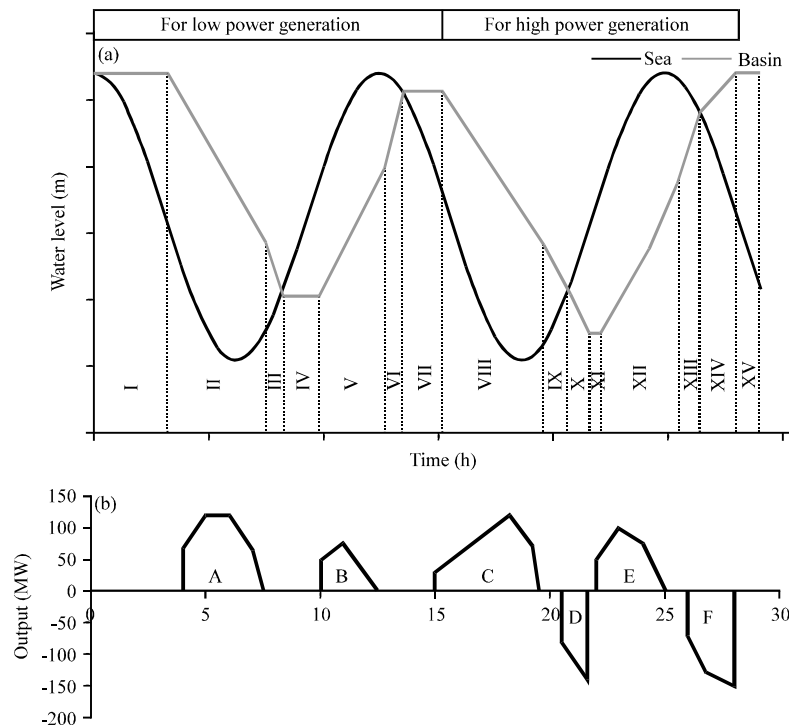

Fig. 1(a-b): La Rance operation modes (De Laleu, 2009), (a) I: Standing, II: Ebbing, III: Emptying, IV: Standing, V: Flooding, VI: Filling, VII: Standing, VIII: Ebbing, IX: Emptying, IX: Emptying, X: Reverse pump operation, XI: Standing, XII: Flooding, XIII: Filling, XIV: Direct pump operation and XV: Standing and (b) A: +392 MWh, B: +174 MWh, C: +385 MWh, D: -120 MWh, E: +245 MWh and E: -230 MWh

turbine gates are opened to allow generation during the low tide until the head falls to the requisite value. This process is the major contributor to the generation of tidal power in a given cycle and is employed for peak demand (Chir and Roberts, 2009).

Emptying: Ebb generation continues till a point where there is a sufficient difference in levels of sea and basin head is available. After this level, the sluice gates are opened to allow for a natural gradient and water flows to empty the basin till the head difference attains zero value. This process is further supplemented by gates as well as an application of negative pumping.

Pumping: Pumping used in tidal power plant is categorised as positive and negative:

Positive pumping: This process begins as the sluice gates are closed after flood generation and filling. Then water is pumped from the sea into the basin which effectively increases the head for generation later on in the cycle

Negative pumping: This is a reverse pumping process when the water level is just falling in the basin. Differential head increases and water is pumped from the basin to the sea thereby generating power in the lean period as well (Shaw and Watson, 2003)

Standing: The basin level remains static during this period and the differential head available is not sufficient enough to generate power on an economically feasible basis.

Flood generation: In this method, the lower half of the basin is filled first and which has a lesser volume as compared to the upper half of the basin. The basin is filled through turbines which generate power at tide flood. As the volume of flow is less, the available head difference between the basin and sea side of the barrage reduces more quickly thereby making it less efficient than the ebb generation. Thus it is a minor contributor to the power generation and caters to the off-peak demand more.

Filling: This process is analogous to the emptying process. Flood generation also continues till a threshold point where a sufficient head is present. Below this value of head difference, power generation is not economical. The gates are kept open to allow high tide sea water to flow into the basin naturally until the levels equalise. Positive pumping supplements the process of filling of basin.

Methodology: The Sihwa tidal plant currently utilizes flooding as the mode of operation as its main purpose was to provide ample amounts of water for its agricultural and industrial land reclamation. Our proposed methodology takes into account the increasing demand of power for the populated inhabitations nearby and hence aims at increasing the power generated form the present basin area by employing the techniques mentioned in the literature review section, currently being employed efficiently at the Rance Power plant. The details of the modifications have been discussed below.

Present working: The location of Lake Sihwa encompasses a favourable basin area of 43 km^2 and experiences a mean tidal range of 5.9 m. The favourable mean spring tide reaches a value of
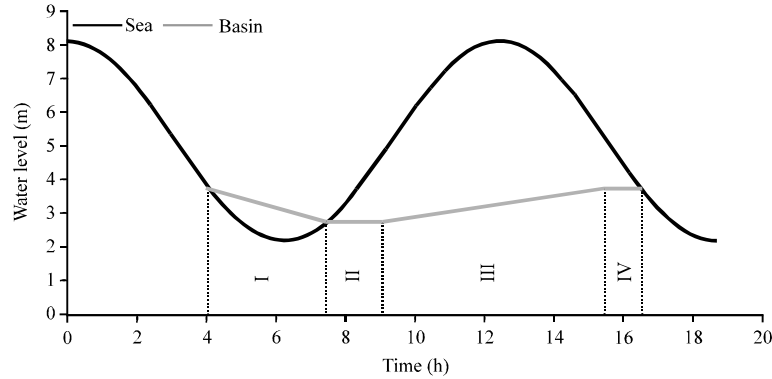
Fig. 2: Existing modes of operation at Lake Sihwa (Bae *et al.*, 2010), I: Emptying, II: Standing, III: Flood generation, IV: Standing

7.8 m whereas the neap tide (These tides occur when the gravitational pull of the Sun counters the pull of the moon due to their relative spatial orientation and this phenomenon occurs twice a month) attains a mean value of 3.3 m. The plant currently employs the methodology shown in Fig. 2 which is predominantly based on flood generation. The processes of emptying and standing enhance the differential head before power generation takes place by the process of flood generation. Employing the existing methodology, the plant is expected to generate 550 GWh of electricity annually (Bae *et al.*, 2010).

Proposed model: Initially based on the trend of daily tide pattern, an empirical relation has been developed. The mean value of tidal water is assumed to follow a sinusoidal variation and can be written as:

$$H_S = \left[2.95 \cos \left\{ \frac{2\pi t}{12.4167} \right\} \right] + 5.15 \tag{1}$$

where, H_S represents the tidal water level in meters, t represents time in hours, thus flow rate into turbine can be expressed as:

$$Q = \left| \left(\frac{\partial H_R}{\partial t} \right) A \right| \tag{2}$$

where, H_R represents the reservoir level in meters A represents basin area (Ferreira and Estefen, 2009):

$$\text{Energy (E)} = \rho g \int Q H_b dt \tag{3}$$

where, H_b is the differential head in meters as:
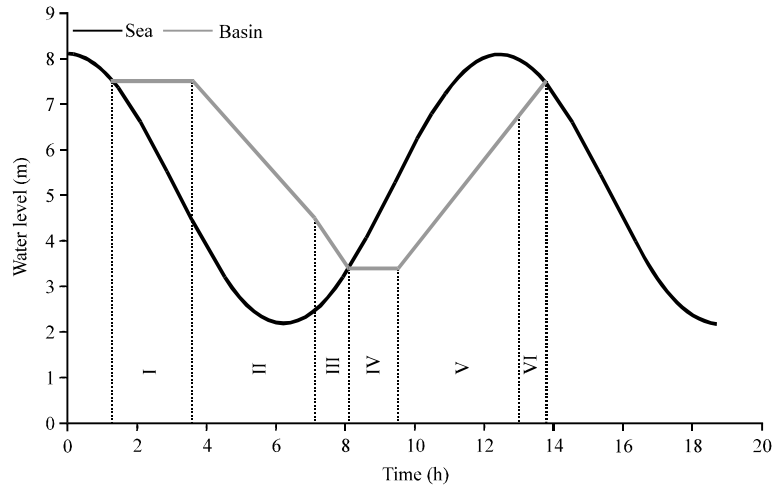
$$H_b = | H_S - H_R | \tag{4}$$

Fig. 3: Proposed modes of operation at Lake Sihwa-without pumping, I: Standing, II: Ebb generation, III: Emptying, IV: Standing, V: Flood generation and VI: Filling

Density of sea water, acceleration due to gravity and number of tidal cycles per year has been assumed as ρ 1025.3 kg m^{-3}, g = 9.81 m sec^{-2} and 706, respectively.

Ebb+flood generation: Generation with Ebb and flood separately as well as together have been discussed below for estimation of total generation.

Ebb only: Differential head between basin and sea leads to the power generation when water flows from basin to sea through turbines (Fig. 3).

The reservoir level can be expressed as (function of time), H_R = 10.87-0.9t. From Eq. 2 we get:

$$Q = \left| \left\{ \frac{\partial(10.87 - 0.9t)}{\partial t} \right\} A \right|$$

From Eq. 1 and 4 as well as the value of reservoir level from above, the differential head can be expressed as:

$$H_b = \left| 5.72 - 0.9t - 2.95\cos\left\{ \frac{2\pi t}{12.4167} \right\} \right|$$

Thus making use of Eq. 3 and the values calculated above we can obtain the:

$$\text{Energy (E)} = \rho g \int_a^b (0.9\,A) \left(5.72 - 0.9t - 2.95\cos\left\{ \frac{2\pi t}{12.4167} \right\} \right) dt$$

where, the limits of integration 'a' and 'b' represent the starting and ending of the Ebb generation period. The energy produced can be estimated as:

$$\therefore \text{Energy (E)} = 1025.3 \times 9.81 \times 0.9 \times 43 \times 10^6 \times 11.09 \text{ Joules}$$
$$= 4.3 \times 10^{12} \text{ Joules}$$
$$= 847.2 \text{ GWh year}^{-1}$$

Taking capacity factor as 40%, we get the annual output = 339 GWh.

Flood only: Differential head between basin and sea leads to the power generation when water flows from sea to basin through turbines (Fig. 3).

The reservoir level can be expressed as (function of time), $H_R = 0.96t\text{-}5.7$.

From Eq. 2 we get:

$$Q = \left| \left\{ \frac{\partial(0.96t - 5.7)}{\partial t} \right\} A \right|$$

From Eq. 1 and 4 as well as the value of reservoir level from above, the differential head can be expressed as:

$$H_b = \left| 2.95\cos\left\{ \frac{2\pi t}{12.4167} \right\} + 10.84 - 0.96t \right|$$

$$\therefore \text{Energy (E)} = \rho g \int_a^b (0.96A) \left(2.95\cos\left\{ \frac{2\pi t}{12.4167} \right\} + 10.84 - 0.96t \right) dt$$

$$\therefore \text{Energy (E)} = 1025.3 \times 9.81 \times 0.96 \times 43 \times 10^6 \times 7.647 \text{ Joules}$$
$$= 3.175 \times 10^{12} \text{ Joules}$$
$$= 623 \text{ GWh year}^{-1}$$

Taking capacity factor as 40%, we get the annual output = 249 GWh. Hence, total yearly output of the proposed working scheme = 339+249 GWh = 588 GWh.

Hence, the increase in the output of the plant:

$$\text{Increment} = \left\{ \frac{(588 - 550)}{550} \right\} \times 100 \%$$
$$= 6.9\%$$

Ebb+flood generation+pumping: Now generation with flood and ebb has been analysed using pumping as presented in Fig. 4.

Ebb only: Differential head between basin and sea leads to the power generation when water flows from basin to sea through turbines (Fig. 4). The reservoir level can be expressed as (function of time), $H_R = 12.28\text{-}1.066t$. From Eq. 2 we get:

$$Q = \left| \left\{ \frac{\partial(12.28 - 1.066t)}{\partial t} \right\} A \right|$$

From Eq. 1 and 4 as well as the value of reservoir level from above, the differential head can be expressed as:
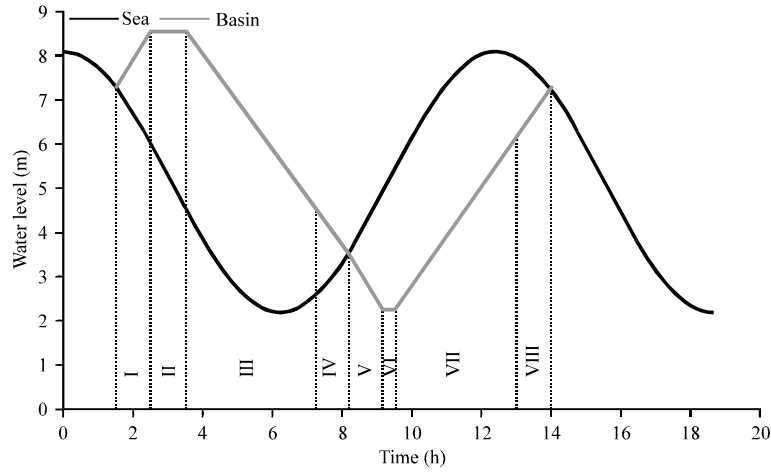
Fig. 4: Proposed modes of operation at Lake Sihwa-with pumping, I: Positive pumping, II: Standing, III: Ebb generation, IV: Emptying, V: Negative pumping, VI: Standing, VII: Flood generation, VIII: Filling

$$H_b = \left| 7.13 - 1.066t - 2.95\cos\left\{\frac{2\pi t}{12.4167}\right\} \right|$$

Thus making use of Eq. 3 and the values calculated above we can obtain the:

$$\text{Energy (E)} = \rho g \int_a^b (1.066\,A)\left(7.13 - 1.066t - 2.95\cos\left\{\frac{2\pi t}{12.4167}\right\}\right) dt$$

$$\therefore \text{Energy (E)} = 1025.3 \times 9.81 \times 1.066 \times 43 \times 10^6 \times 14 \, \text{Joules}$$

$$= 6.454 \times 10^{12} \, \text{Joules}$$

$$= 1266 \, \text{GWh year}^{-1}$$

Taking capacity factor as 40%, we get the annual output = 506 GWh.

Flood only: Differential head between basin and sea leads to the power generation when water flows from sea to basin through turbines (Fig. 4).

The reservoir level can be expressed as (function of time), $H_R = 1.112t-8.319$. From Eq. 2 we get:

$$Q = \left| \left\{ \frac{\partial(1.112t - 8.319)}{\partial t} \right\} A \right|$$

From Eq. 1 and 4 as well as the value of reservoir level from above, the differential head can be expressed as:

$$H_b = \left| 2.95\cos\left\{\frac{2pt}{12.4167}\right\} + 13.47 - 1.112\,t \right|$$

$$\therefore \text{Energy (E)} = ?g \int_a^b (1.112\,A)\left(2.95\cos\left\{\frac{2pt}{12.4167}\right\} + 13.47 - 1.112t\right) dt$$

$$\therefore \text{Energy (E)} = 1025.3 \times 9.81 \times 1.112 \times 43 \times 10^6 \times 11.574 \, \text{Joules}$$

$$= 5.56 \times 10^{12} \, \text{Joules}$$

$$= 1092 \, \text{GWh year}^{-1}$$

Taking capacity factor as 40%, we get the annual output: = 437 GWh.

Pumping:

- The pumping technique has been employed under the two broad processes of positive (region I) and negative pumping (region V) as depicted in Fig. 4. The approach is described below:
- A 1 h pumping process to raise the level of 22 km^2 of basin area by a height of 1.5 m requires an input of 120 MWh in the Rance power plant
- The total energy can be summed up as follows:

$$\therefore \text{Energy (E)} = \left\{ \frac{\rho g A H^2}{2} \right\}$$

- Equating the values pertaining to the operations at the La Rance power plant. Taking a cycle period of 1 hour, the power thus required is 120 MW
  $\therefore$ For energy (E), efficiency of the pump η and 'A' being the area of basin, we have:

$$E\ (J) = \left\{ \frac{1025.3 \times 9.81 \times 22 \times 10^6 \times 1.5^2}{2} \right\}$$

Also (E) = $120 \times 10^6 \times 3600 \times \eta$ Joules. Hence, η = 57.62%.
- For the values pertaining to the proposed site operations. Taking a cycle period of 1 h, the power required is 120 MW, We have:

$$E\ (J) = \left\{ \frac{1025.3 \times 9.81 \times 43 \times 10^6 \times 1.25^2}{2} \right\}$$
$$= 3.379 \times 10^{11}$$

Now taking into account the pump efficiency as calculated above, the actual pumping energy required will be greater by a factor of η = 0.5762.

Moreover, since the methodology of positive as well as negative pumping in a single generation cycle has been utilized, the gross pumping energy required:

$$
\begin{aligned}
E_{actual} \quad &= \quad (162.9 \times 2) \text{ MWh per tidal cycle} \\
&= \quad 325.8 \text{ MWh per tidal cycle} \\
&= \quad 120 \text{ GWh per year}
\end{aligned}
$$

Total yearly output of the proposed working scheme = (506+437)-230 GWh
  = 713 GWh

As is evident there is an even more marked increase in the output of the plant on employing the dual techniques:

$$\text{Increment (\%)} = \left\{ \frac{713 - 550}{550} \right\} \times 100$$
$$= 29.63\%$$

The above value includes a certain increase over and above the methodology of ebb and flood generation only. Pumping thus contributes as follows:

$$\text{Increment (\%)} = \left\{ \frac{713 - 588}{588} \right\} \times 100$$
$$= 21.25$$

Proposed machinery: In the two proposed models discussed above the bulb turbines in the barrage can be used to pump extra water into and out of the basin at periods of no generation. For power generation using only ebbing and flooding mechanisms 18 bulb turbines each of capacity 21.8 MW at maximum operating differential head of 3.637 m and a discharge of 600 cubic m sec^{-1} are used. Similarly for power generation using pumping, 23 bulb turbines each of capacity 23.67 MW at maximum operating differential head of 4.252 m and a discharge of 553.6 cubic m sec^{-1} are used.

CONCLUSION

Hence, by incorporating COMBINED EBB and FLOOD type generation, an increment of 6.9% is achieved over present annual power output of 550 GWh. Moreover by incorporating PUMPING along with it, the annual output can be enhanced by 29.6% which means an additional increment of 21.25% in annual power output is achieved incorporating pumping additionally.

But before going ahead with any enhancements, the merits and limitations of these modes of operations have to be seen so that they are economically and ecologically feasible. For example, if the basin area A is very large, then the pumping operation may not be economically viable. These are only a few facets leading to an increase in power output but there is tremendous potential for application of other beneficial techniques such as a multiple basin/reservoir scheme, improved turbine designs which not only enhance efficiency but also mitigates the damage caused to aquatic life. By careful observation of the cyclic variations of the differential head and the variations in demand over and above a constant value, a co-ordination can be achieved which results in maximum power generation during the ebb generation period when there is a peak demand. As the ebb period starts after around two hours of the high tide, the timing can be adjusted to synchronize with the demand requirements.

The Gulf of Khambhat located on the western coast of India with a massive basin area of 1970 km^2 has a huge potential with a mean tidal range of 6.7 m; the site may result in an annual capacity of 15 TWh of energy on application of the modes of operation stated above. The proposed machinery is for maximum operating differential head and maximum utilisation of turbine generation as well as pumping capacity. For lower demand requirements and accounting for the capacity factor, the power requirements in actual operations will be less than the maximum and hence, lesser turbines will be in operation.

REFERENCES

Bae, Y.H., K.O. Kim and B.H. Choi, 2010. Lake Sihwa tidal power plant project. Ocean Eng., 37: 454-463.

Chir, A. and I. Roberts, 2009. Very low head Bi-directional tidal barrage presentation. North West Tidal Energy Group.

De Laleu, V., 2009. La Rance tidal power plant. 40-year operation feedback-lessons learnt. Proceedings of the British Hydropower Association Annual Conference, October 14-15, 2009, Liverpool, UK., pp: 1-40.

Expert Group on Renewable Energy, 2005. Increasing global renewable energy market share: Recent trends and perspectives. Renewables 2005 Background Report, UN Department of Economic and Social Affairs.

Ferreira, R.M. and S.F. Estefen, 2009. Alternative concept for tidal power plant with reservoir restrictions. Renewable Energy, 34: 1151-1157.

Muzathik, A.M., W.B.W. Nik, M.F. Ahmad, M.Z. Ibrahim, A.H. Sharuddin and K.B. Samo, 2011. Ocean wave properties of Terengganu for renewable energy potential. J. Applied Sci., 11: 1895-1903.

Shaw, T.L. and M.J. Watson, 2003. The effects of pumping on the energy potential of a tidal power barrage. Institution of Civil Engineers. Eng. Sustainabil., 156: 111-117.