

A review on tidal power utilization and operation optimization

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Abstract. Tidal power, provided by the gravitational attraction of the moon and the sun, releases massive amount of reusable energy around the world. To utilize this natural energy resource, tidal stations were built worldwide, transforming tidal power into electricity with reservoirs and tidal turbines. This review article summarizes the distribution and current utilization of tidal power around the world, and, particularly, in China. Contemporary tidal power utilization is sketched with a detailed description of several tidal power stations. And then, the major types of tidal turbines in use are introduced including the bulb tubular unit, rim generator unit, cross flow unit etc. Comparing these tidal turbines, their advantages and defects under different circumstances are pointed out and some directions for future modifications are proposed. Apart from raising power transformation efficiency through elaborate turbine design, to further exploit tidal power, the optimization of station operation is also essential. In this article, the operation features of the tidal station are described in detail and the current methods of optimization are reviewed.

Keywords: Tidal Power Utilization, Tidal Turbine Design, Operation Optimization

1. Introduction

In response to the global concern over fossil fuel consumption and global warming, reusable energy technologies are becoming increasingly favored alternatives. Amongst the proposed alternative natural energy resources, the utilization of many face the challenge of being unpredictable, including solar energy, wind power, and wave power, which are strongly affected by weather conditions [1]. Tidal power, on the other hand, is relatively predictable, being nearly periodic, twice a day in most areas and once a day in some places, with calculable fluctuation over the solar and lunar cycle. Potentially, with a 3 TW total energy flux of the tides worldwide and about 1 TW available at shallow waters, tidal power has the prospect of satisfying a considerable percentage of global electricity demand [2]. However, with the current technologies, only a small percentage can be harnessed in the near future because the tidal energy is widespread along the global coastlines.

At present, most tidal power stations use tidal barrage techniques to store and generate tidal power, in such a station a dam is placed across an estuary or along the coast, on which tidal turbines are installed. The turbines may operate one way or both ways and pumps may also be installed to store energy in the reservoir [3]. There have also been proposed another way of



extracting kinetic energy from the ocean, namely through tidal current turbines which gather the kinetic energy of the waves vertically and horizontally. However, in this fashion the turbine gathers only the simultaneous kinetic energy of the wave instead of the periodic height difference provided by the tidal range. This article mainly restrict discussion to the tidal barrage operation mode which is preferred in most power stations.

This article contains four sections from which a rough picture of current tidal power usage is presented. First the global picture of tidal power distribution along the coastlines, the current tidal power plant coverage and discuss in detail several operating tidal stations are introduced. In the second section, several turbine designs are compared and some modifications proposed. The third part is an introduction of the operation sessions in a tidal barrage power plant and the current methods of the optimization of the station operation. Finally, some current difficulties in the actual running of the stations are pointed out and an outlook on future directions of tidal power exploitation and related research is proposed.

2. Tidal Power Distribution and Current Utilization

Tidal barrage stations are usually installed near coastlines where the tidal range is sufficient for commercial electricity generation since the energy generated is proportional to the tidal amplitude squared. In Europe, the potential tidal energy resource is estimated to exceed 12 GW of installed capacity [4]. Ideal locations with immense currents are found around the coasts of the British Islands and Ireland, between France and the Channel islands, around in Aegean and in the Straits of Messina between Italy and Sicily. There is also prediction of about 90 Gw potential tidal energy along the North West coast of Russia and 20 GW at the inlet of Mezen River into the White Sea [5]. In Asia, China holds a theoretical potential of 13.9 GW unevenly distributed tidal power with about 7 GW around the Estuary of Yangtze River in Zhejiang and Jiangsu Province [6], the West Coast of India is estimated to potentially generate 8 GW of tidal power [5]. Other locations with high tidal amplitudes around the world include the west coast of Malaysia and the Philippines, the west coast of Australia, the East and West coasts of Canada and many other places. The figure below from NASA shows a global semidiurnal tidal amplitude distribution. Although the global reserve of tidal power is tremendous, currently only few locations are exploited.

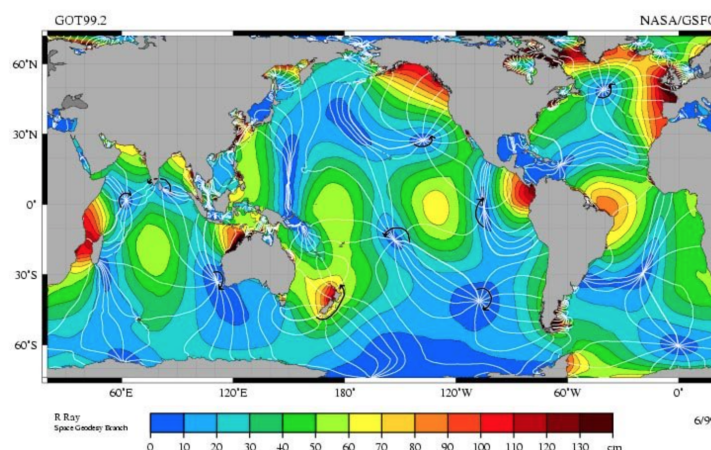


Figure 1. Distribution of semidiurnal tidal amplitude around the world (https://en.wikipedia.org/wiki/File:M2_tidal_constituent.jpg)

2.1. Tidal Range Power Plants

Most tidal range stations are situated across major rivers or lakes and consists of several generating units, sluice gates and other structures including ship locks, tourist areas etc.. The following pictures are demonstrations of the construction of the La Rance Tidal Station and Shihwa Lake Tidal Station.

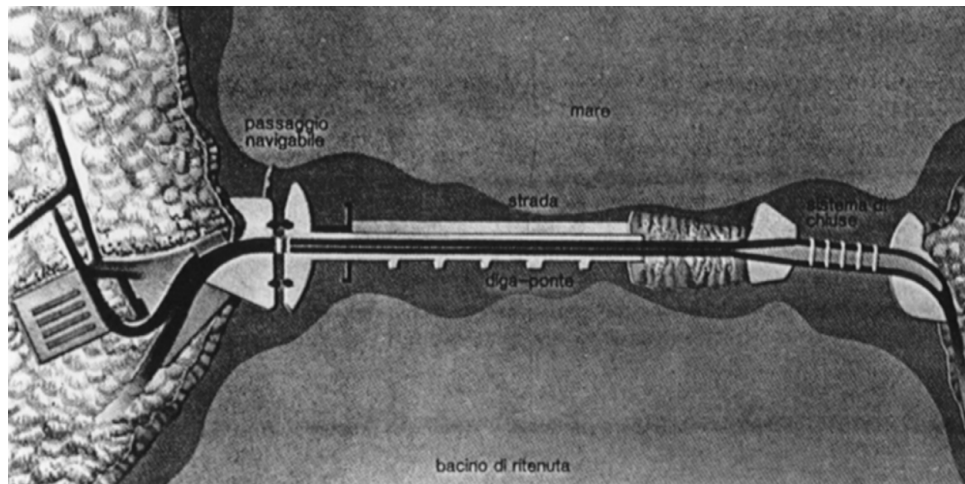


Figure 2. Ariel View of La Rance Tidal Station[7]

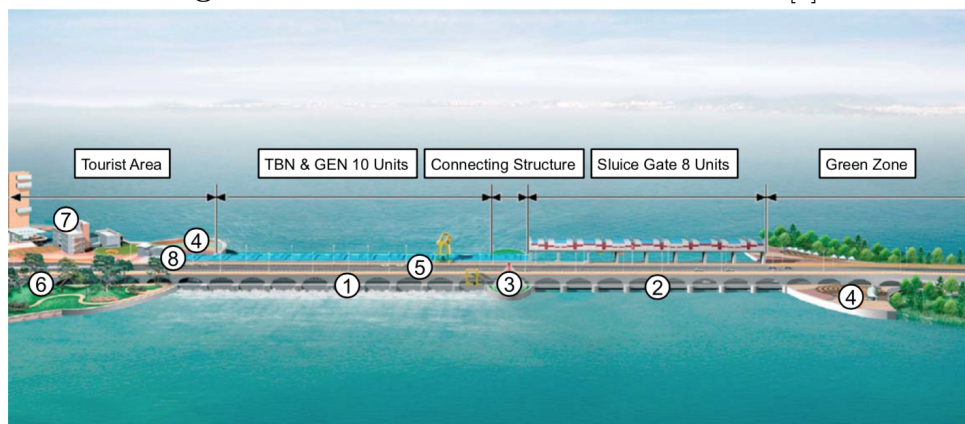


Figure 3. Construction Plan for Shihwa Lake Tidal Station[8]

Up to now only five commercial scale tidal range stations are in operation, their main factors are shown in Table 1 (sorted by year of operation).

There are also several tidal range power plants under development and future plans undergoing investigations around the world. Some major plans are shown in Table 2 [12], and those in China are as shown in Table 3.

More precisely, the Swansea project in U.K. is actually a tidal lagoon project: the first proposed in the world. The design is similar to tidal range stations, except that it can be placed arbitrary in the shallow waters, enclosing a basin [13].

Table 1. Main factors of commercial scale tidal range stations in use.

Station Name	La Rance[7]	Kislaya Guba[9]	Jiangxia[10]	Annapolis[11]	Sihwa[8]
Country	France	Russia	China	Canada	South Korea
Capacity(MW)	240	1.7	3.9	20	254
Ann. Output(GWh)	540		6.5	30	553
Year	1966	1968	1980	1984	2015
Turbine Number	24	1	6	1	10
Turbine Type	Bulb	Savonius	Bulb	Rim	Bulb
Basin Area(km ²)	22	1.1	1.4	15	56
Mean Tide/m	8.5	2.3	5.1	6.4	5.6

Table 2. Major plans for tidal range stations.

Station Name	Country	Capacity(MW)	Commission	Mean Tide(m)	Basin Area(km ²)
Incheon	South Korea	1320	On hold	5.3	110
Swansea	U.K.	320	2019	/	11.5
Severn	U.K.	8640	Proposed	7.8	450
Mezen	Russia	19200	Proposed	9.1	2300
Penzhin	Russia	87000	Proposed	9	20,530

Table 3. Construction plan and application in China.

Station Name	Province	Capacity(MW)	Max. head (m)	Min. head (m)	Ave. head (m)
Maluanwan	Fujian	24	6.69	1.50	2.58
Bachimen	Fujian	36	7.55	1.15	3.10
Jiantiaogang	Zhejiang	21	5.57	1.18	2.63

3. Case Studies

3.1. La Rance Tidal Power Station

The first and, so far, second largest tidal station was successfully constructed on the Rance Estuary in Brittany, France in 1966, with an 8.5 m mean tide, it holds an installed capacity of 240 MW and produces an annual output of 520 GWh, sufficient for 4 % of the homes in Brittany. The construction cost was 95 million Euros in 1967, equivalent to an electricity cost of approximately 1.8 cents per kWh in 2009. The barrage contains of a 115 m long weir with sluices to accelerate the filling and emptying of the basin at small water head, a long section of bays (332.5 m) housing 24 reversible bulb turbines, and also a ship lock [7] [14].

The stations operate in various modes. It can perform two-way generation (mostly ebb generation) and forward pumping (into the reservoir) in which 56 % of the time the turbines

generate forward, 11.7 % of the time it generates backward, 14.7 % of the time is on direct pumping, 1.4 % on reverse pumping and 16.2 % of the time water flows freely into the basin. It can also operate one-way only generating in the ebb tide [7].

From 1966 till now, the station experienced few technical problems except in 1975, the generators were found stressed due to asynchronous starts up during pumping phases and were rebuilt [14].

3.2. Jiangxia Tidal Power Station

Jiangxia station, constructed near the mouth of Yalu River in Wuyantou, Zhejiang Province was put into operation in 1980 holding an installed capacity of 3.9 MW and an annual output of 6.5 GWh. The barrage contains 5 sluice gates and 6 turbine generators of 4 different types: two 545 kW and 659 kW bulb turbines of 118 rpm with gearbox, put to operation in 1980 and 1984, three 600 kW bulb turbines of 125 rpm direct drive put to operation in 1985 and a 700 kW direct drive was installed in 2007 [15].

3.3. Haishan Tidal Power Plant

Haishan power plant is a demonstration of local small-scale tidal station. It is located on the Maoyan Island in Zhejiang Province China and came into operation in 1975. It is a double basin barrage of basin area 0.23 and 0.008 km², with the power plant in between the two. The turbines generate one way, offering an installed capacity of 250 kW and produces an annual output of 340 MWh, serving an isolated community of 760 families on the island.

The operation of the power plant has been successful since 1975, except that it has suffer great siltation problems [10].

4. Turbine Designs

Turbine design is a crucial element for electricity generation in tidal barrages since it determines many of the operation constraints including flow rate, head variance and range, start-stop frequency and whether two-way generation is possible.

4.1. Bulb Turbine

Bulb turbines are the most commonly used turbine design for tidal stations because of their high efficiency (maximum efficiency exceeding 90 %) for low head, their relatively small volume and lower cost, and also because they are reversible, generating power on both the flood and ebb tides. A prominent problem with bulb turbines in tidal stations is that the maintenance of the turbine or generator requires the structure to be lifted off the water and stop production [16].

The bulb turbine and generator are placed together in the middle of the water passageway along the horizontal axis. The name came from the bulb-shaped upstream casing containing the generator. A demonstration of the unit in La Rance Tidal Station is shown below.

To achieve higher efficiency in flood phase generation, a modified version of bulb turbine introducing a second set of guide vanes was proposed. A theoretical test [17] found an improvement of flood phase efficiency from 69.64 % to 80.12 % and a relatively low drop in the forward direction from 84.03 % to 80.12 % when adding the extra guide vanes. The modified turbine was also tested at Wanapum Dam where it found a higher sheer stress in the wakes (harmful to fish) which potentially poses greater environmental impact [18].

Luo et al [19] has also introduced an optimization procedure for low-head bidirectional tidal bulb turbine runner to modify bulb turbine design under given working condition. The optimization methods introduced is said to improve the modeled turbine efficiency by 5.5 % (ebb) and 2.9 % (flood) for a four bladed turbine and 4.3 % and 4.5 % for a three-bladed turbine. In addition, a numerical method to predict accurately the prototype hydraulic performance was proposed with the upstream reservoir modeling, for low-head bulb turbine operation [20][21].

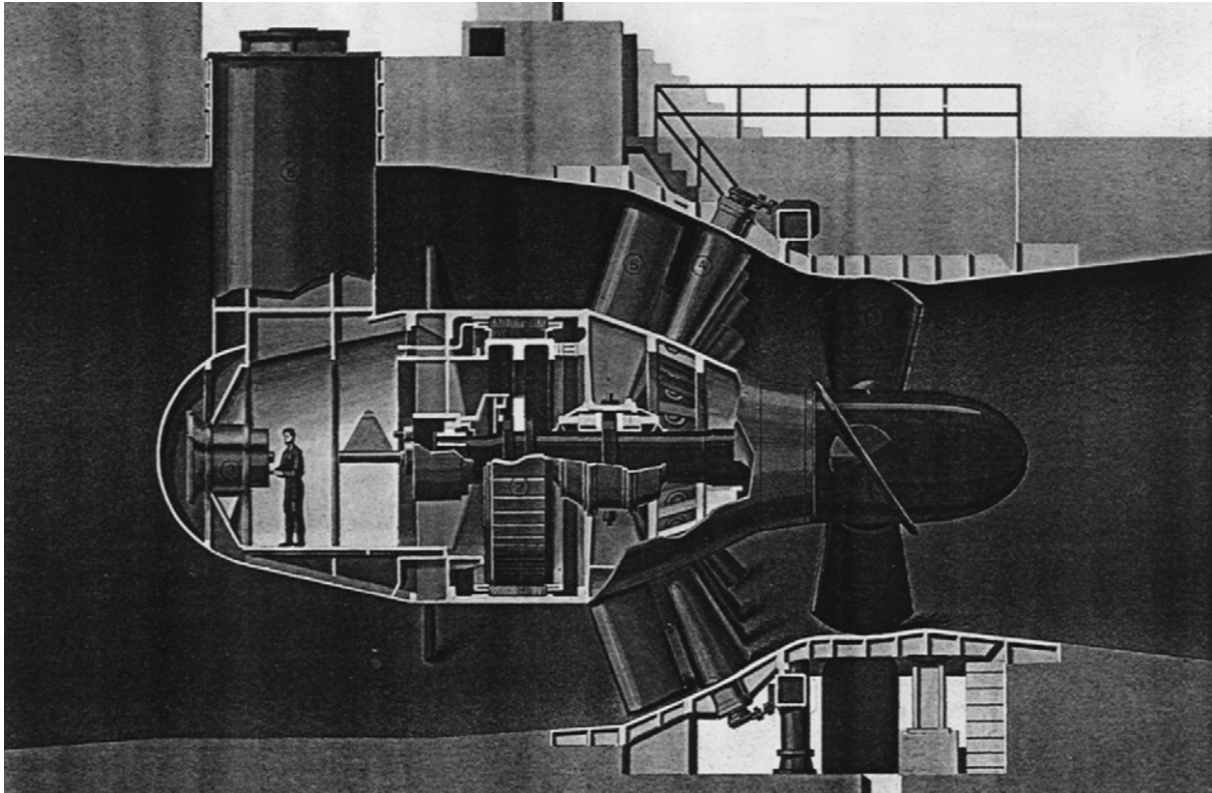


Figure 4. Bulb Turbine Design[7]

4.2. Rim Turbine

Rim turbine is designed with the motor rotor attached to the outer ring of the turbine runner and the motor stator inside to the Rim turbine is designed with the generator rotor attached to the outer ring of the turbine runner and the generator stator inside to the infrastructure. It behaves better under continuously changing head of the tidal station and is cheaper and easy to install and maintain. Theoretically, it has greater inertia (thus better stability). However, it can only operate on the ebb tide and cannot be used for pumping [22].

The largest rim turbine unit in tidal stations up to now is in the Annapolis tidal station in Canada. It has a rated power of 17.8 MW and a diameter of 8.2 m, with rated efficiency of 89.1 % and operation efficiency 87.3 %. The generator has 144 pole attached to the outer surface of the runner, and the stator has a diameter of 13m submerged in the concrete. The generator is equipped with an air cooler for cooling. The unit is mostly made of carbon steel and partly stainless steel, using cathodic protection to avoid corrosion [23]. It is also reported that the rim turbine in Annapolis kills a great number of fish and studies are done on devising fish diversion system in the station [24].

4.3. Other Turbine Design for Tidal Range Generation

Apart from the mostly commonly used bulb generating unit and rim generating unit, there are also other simplified designs considered for tidal range generation, including the Savonius turbine in operation in Kislaya Guba Tidal Station [25], tubular turbine which is better suited for low head conditions and also the Banki turbine for both tidal range and tidal stream generation.

The Savonius turbine unit has a round runner with usually 2 to 4 blades and is deployed horizontally or vertically, with the spindle orthogonal to the water passageway. Then, generator

can be deployed out of the water passageway with little restriction on its size and rotation speed. With its simple structure it is easier to manufacture and to maintain. However, its efficiency is not as high as bulb or rim units and drops under variable head of the tides. The Kislaya Guba tidal station which originally operated with a 400 kW bulb turbine [26] has been upgraded to an experimental Savonius turbine since its upgrade in 2006 [27].

In a tubular turbine unit, the rotation axis of the turbine and generator are at some angle with the water inflow, so the generator is placed outside the water passageway. The blades are connected to a long shaft so it can be easily adjusted throughout the generating process. Its structure allows for minimum volume of the gearbox which reduces the hydraulic loss in operation. Maintenance of the generator is also easier to carry out. However, tubular turbines present more vibration problems [27].

Banki Turbine is invented by Hungarian Professor D. Banki in 1912 and modified by Australian engineer A. G. Mitchell and belongs to the family of crossflow turbines [28]. Water flows in to the turbine vertically, turns at the axis and flows out again, hitting the blades twice on its way. With its simple structure. It can apply to low head conditions including tidal range and tidal stream stations. However, its efficiency is relatively low so it is better suited for small tidal units under 300 kW [10].

5. Operation Optimization for Tidal Range Generation

For tidal range generation, the timing and adjustment of the operation is also important for the generation of more electricity and the maintenance of the turbines and generators. This section introduces the operation phases of tidal range stations and the current approach to its optimization.

5.1. Operation Process and Phases

The operation of a tidal station usually follows the half-day cycle of the tides. For a two-way generating station, during ebb tides, the turbines generate forward until head is too low. And then, the turbines are closed off, sluices opened to accelerate the falling of basin water level. Pumping is applied for some time when sea level rises higher than the basin water level and then stopped and the sluices closed. When the tide rises the turbine runs reverse until the head drops till the turbines has to be closed off. And then, water flows freely into the basin until basin level is higher than sea level and forward pumping is applied. The pumps and sluices are closed off again until sea level drops till ebb generation is applied again returning to the first phase [11]. Depending on the turbine design, pumping may only be required in once in a cycle or not at all, and only one of ebb and flood generation may be applied. The following pictures are the actual operation of Sihwa tidal station and Jiangxia tidal station.

5.2. Optimization Methods

Throughout the years, many scholars have explored the methods of optimizing the operation of tidal range generations [12].

Given the tidal conditions of the sea, the plant operation phases based on the structure and turbine, neglecting the barrage's influence on the tidal conditions, the 0D modeling gives a simulation of the basin water level change and energy production according to time [30][31]. Based on the 0D modeling, Prandle et al. [30] solved the optimization using analytical approach through some simplifications including a single tidal constituent and a constant turbine discharge rate. Numerous calculations have been done by computer programming seeking to find the optimal generation start and stop time of each phase [32][33]. The numerical approach however, is computationally expensive and is dependent on the random fixed starting head [34].

Higher dimensional modeling considering the hydrodynamic impact of the station on the system to estimate the power outcome? have also been considered. For barrage across an

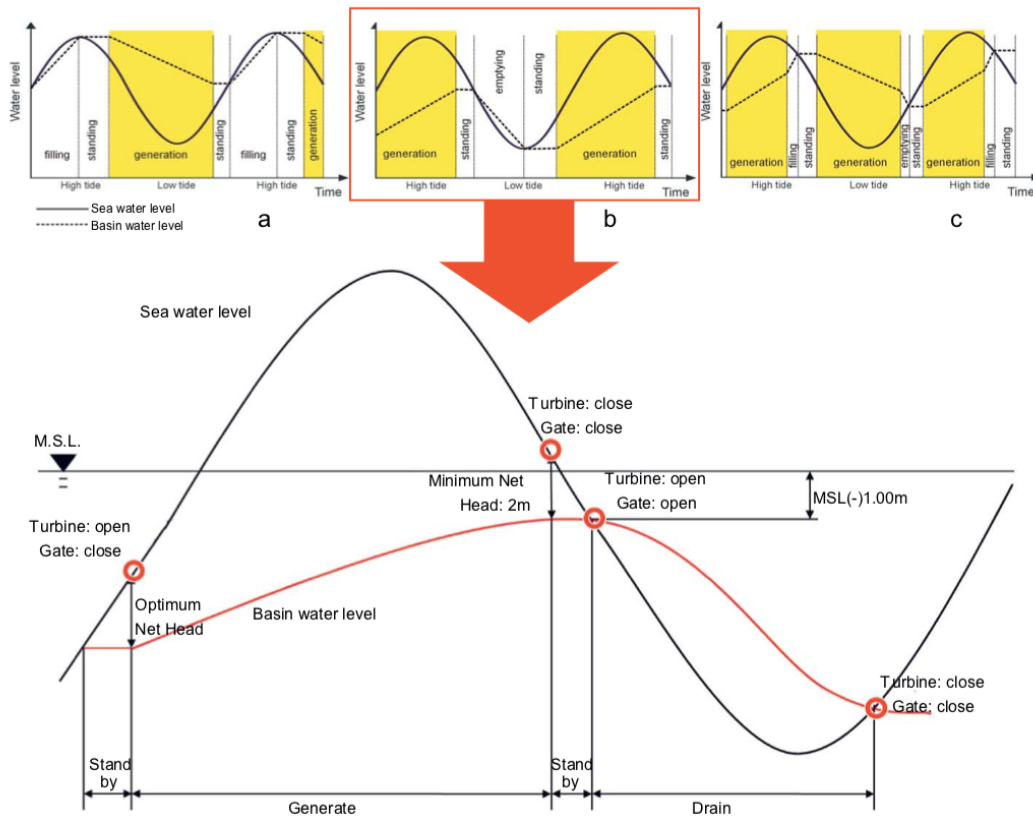


Figure 5. Operation of Sihwa Tidal Station[8].

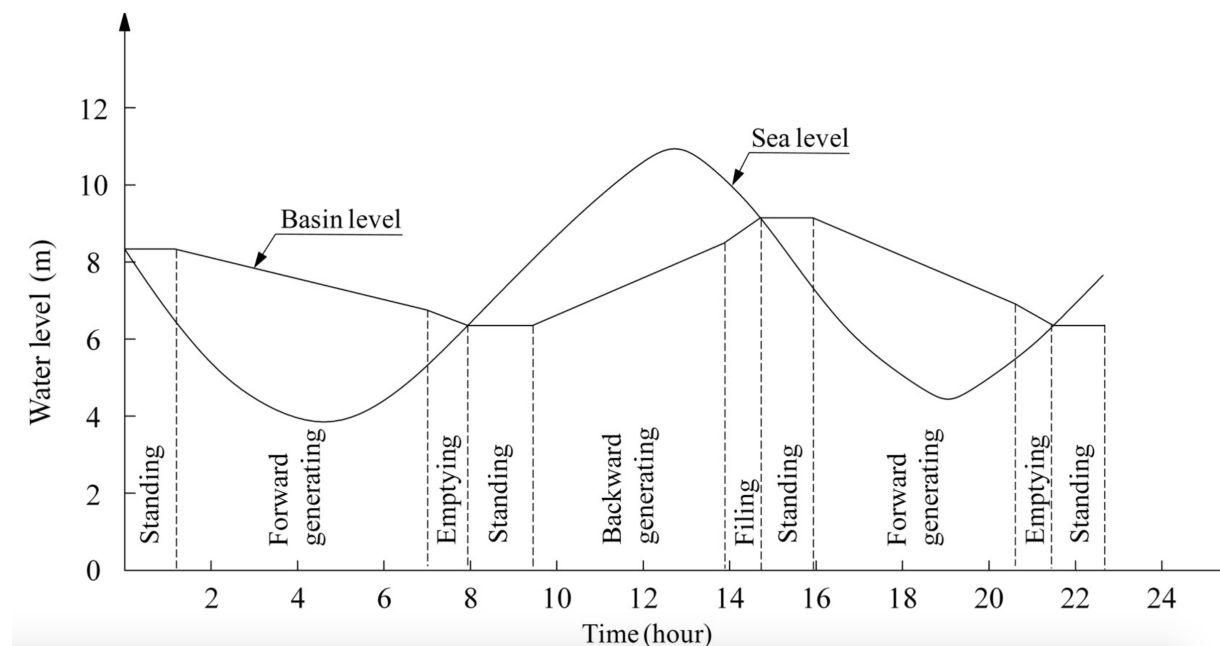


Figure 6. Operation of Jiangxia Tidal Station[29].

estuary, 1D modeling can be applied to include the flow across the estuary to capture the changes the operation of the station bring on the tides. Semi-analytic model were given on specific sites, e.g.[35] and some numerical solutions were provided [36]. 2D and 3D models are also introduced. For larger scale stations, the 2D model uses the depth-averaged shallow water equations derived from depth-integration of Navier-Stokes equations. The 3D model uses the Navier-Stokes equations [37]. Applied to the tidal stations, it can more accurately predict the water levels to calculate the electric output. The higher-dimensional modeling can also be used to evaluate environmental impact of the station and modify station design. However, its calculation is very complicated and is more often introduced to adjust the 0D model rather than to achieve optimization of the station operation [38].

6. Main Challenges and Future Prospect

Currently, for tidal range generation, the turbine design are relatively mature, with efficiency exceeding 80%(maximum efficiency exceeding 90%) and operation running smoothly for decades already. The maintenance and protection of the equipments in the ocean is also basically solved using protective paints, cathodic protections etc. to avoid corrosion and animal adherence. Main challenges now lie with the operation design, the economic viability and environmental influence of the station [39]. One proposed solution to this problem is to construct tidal lagoons, tidal fences and tidal reef instead of traditional barrage [11]. These projects are smaller in scale, using lower head turbines and more flexible in its site selection so that environmental issue can be taken into consideration, and simulations show that they might even has beneficial environmental effect [40].

There are also studies on designing generation methods incorporating both tidal range and tidal stream power(DTPs)[41], or incorporating tidal generation with economic activities including sea water desalination, sea farming and coastal reclamation. These combined technologies may help further decrease the construction costs of tidal stations [2].

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