Applied Energy 212 (2018) 680–690

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimising tidal range power plant operation

Athanasios Angeloudis*, Stephan C. Kramer, Alexandros Avdis, Matthew D. Piggott

Department of Earth Science & Engineering, Imperial College London, UK

HIGHLIGHTS

- We describe numerical methods to simulate the operation of tidal range power plants.
- We couple simplified power plant operation models with gradient-based optimisation algorithms.
- The consideration of a flexible operation with pumping is shown to have the potential to deliver significant energy gains.
- Optimisation of larger plant designs should be coupled with hydrodynamics solvers.

ARTICLE INFO

Keywords:
Tidal range energy
Tidal lagoon
Marine energy
Resource assessment
Control optimisation
Gradient-based optimisation

ABSTRACT

Tidal range power plants represent an attractive approach for the large-scale generation of electricity from the marine environment. Even though the tides and by extension the available energy resource are predictable, they are also variable in time. This variability poses a challenge regarding the optimal transient control of power plants. We consider simulation methods which include the main modes of operation of tidal power plants, along with algorithms to regulate the timing of these. This paper proposes a framework where simplified power plant operation models are coupled with gradient-based optimisation techniques to determine the optimal control strategy over multiple tidal cycles. The optimisation results inform coastal ocean simulations that include tidal power plants to gauge whether the benefits of an adaptive operation are preserved once their hydrodynamic impacts are also taken into consideration. The combined operation of two prospective tidal lagoon projects within the Bristol Channel and the Severn Estuary is used as an example to demonstrate the potential benefits of an energy maximisation optimisation approach. For the case studies considered, the inclusion of pumping and an adaptive operation is shown to deliver an overall increase in energy output of 20–40% compared to a conventional two-way uniform operation. The findings also demonstrate that smaller schemes stand to gain more from operational optimisation compared to designs of a larger scale.

1. Introduction

Tidal range power plants harness the potential energy contained within coastal flows characterised by a high tidal range. Existing and prospective tidal range projects essentially constitute impoundments either in the form of *barrages* that span an entire estuarine basin [1,2], or as *coastal lagoons* positioned against coastlines [3]. These impoundments are designed to facilitate a potential head difference through the carefully orchestrated operation of sluice gates and hydro-turbines, with the latter converting potential energy into electricity. This technology has been gaining momentum, as indicated by a recent UK Government review [4] suggesting that it could make sustainable contributions to the nation's electricity needs in the near future, if developed strategically.

The design and operation of a tidal power plant needs to consider the minimisation of potential environmental impacts [5,2], the maximisation of power output [6] and meeting the electricity demand in a cost-effective manner among other factors. Given the significant capital investment required for the construction of tidal range plants [7] and the nascent status of the technology relative to other electricity generation methods, the optimal operating characteristics must be determined at the design stage enabling an informed quantification of investment risk and return.

The optimisation of tidal range structure operation in response to the time-varying resource represents an important challenge. Numerical simulations are typically used to examine the effect of various parameters on electricity output. However, the problem of determining the optimal operating parameters can be computationally demanding, as simulations must accurately resolve the plant near-field as well as the far-field conditions if the hydrodynamic response of the

---

* Corresponding author.
E-mail address: a.angeloudis06@imperial.ac.uk (A. Angeloudis).

https://doi.org/10.1016/j.apenergy.2017.12.052
Received 14 October 2017; Received in revised form 28 November 2017; Accepted 9 December 2017

flow is to be accurately predicted across all the scales relevant to the problem and for all parameter permutations.

Previous studies of tidal range power, including Prandle [8], Wolf et al. [5], Burrows et al. [9], Xia et al. [10,11], Falconer et al. [12], Cornett et al. [13], generally focused on: (a) conventional ebb-only/flood-only generation or two-way operation without pumping options; and (b) assumed that the operation remained uniform over varying tidal conditions. Very little has been reported in terms of optimisation; the study of Aggidis and Benzon [6] considered that the optimum head difference might vary subject to the tidal range present in an ebb-only strategy, which effectively corresponds to a single-variable optimisation problem. More recently, the optimisation of a simplified two-way operation in tidal power plants was presented by Lisboa et al. [14] heeding lessons from hydro-power scheduling optimisation studies [15]. Only a few control parameters and technical constraints have typically been considered, thus making exhaustive brute-force optimisation methods computationally feasible. Here we seek to build on preceding efforts through the application of an optimisation approach allowing for a far more flexible control of tidal power plant operation.

Current tidal lagoon proposals would likely feature dynamic operation strategies (e.g. bidirectional generation with pumping intervals [16]) that should be accounted for in their assessment. A realistic operation scenario involves a large number of variables, and optimisation using exhaustive variable-space investigations can progressively become computationally untenable. Gradient-based methods are increasingly popular for optimising parameters in complex engineering problems, without a wide exploration of the complete parameter space [17–19]. We present a gradient-based optimisation approach for the adaptive operation of tidal power plants, that is in addition informed by and tested using coastal ocean modelling simulations to account for the effects of the schemes on surrounding hydrodynamics.

2. Methodology

2.1. Tidal power plant operation

The potential energy contained within a head difference H developed across a tidal range structure, neglecting any form of losses, has been investigated by Prandle [8] and quantified as

$$E_{\max} = \frac{1}{2}\rho g A H^2, \tag{1}$$

in J where ρ is the fluid density (kg/m^3), g is the gravitational acceleration (m/s^2), A is the impounded surface area (m^2), and

$$H = \eta_{\mathrm{up}} - \eta_{\mathrm{dn}}, \tag{2}$$

is the head difference developed where η_{up} and η_{dn} correspond to the upstream (i.e. on the inland side of the impounded area) and downstream (outer) water elevation respectively in m. The total amount of energy resource that can be extracted from a tidal power plant in each tidal cycle is related to (a) turbine technology capabilities, (b) the spring-neap (and longer period) tidal variations at the site and (c) the design of the structure and its interaction with local hydrodynamics.

The efficiency of tidal power plants in harnessing the available potential energy during a given tidal cycle is heavily dependent on the control of the constituent hydraulic structures [10,20,9,8,21]. A generalised illustration of how a plant can be regulated is presented in Fig. 1, with $t_i, i = 1,\dots,n$ forming the main control variables. In its simplest form, power generation is one-directional, i.e. it is restricted to either the ebb or flood stages of the tide. For example, in a typical ebb-only (without pumping) generation strategy the active modes of operation according to Table 1 are reduced to a sequence of m = 2, 4, 6 and 7a. In that case the only variable to be determined (following Fig. 1) is t_6, i.e. the holding time at m = 6 prior to power generation (m = 7a). The transitions to m = 2, m = 4 and m = 6 are triggered automatically once the minimum turbine generation head ($h_{\min}$) is reached, for $H < 0$ and $H > 0$ respectively. In order to simulate the operation of such sequences in time, it is essential to parametrise the behaviour of turbines and sluice gates.

2.2. Hydraulic structure parametrisation

The flow through the power plant hydraulic structures is driven by the water head difference H developed between the two sides of the structure. H can be used as input to functions that calculate the instantaneous flow rate from turbines and sluice gates. Sluice gate flow Q_s (kg/m^3) can be calculated as:

$$Q_s(m,H,t) = \begin{cases} r(t)\cdot \mathrm{sgn}(H)\cdot C_d \cdot A_s \cdot \sqrt{2g|H|} & \text{for } m \in \{3b,4,7b,8\} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where A_s is the aggregate cross-sectional flow area (in m^2) of the gates installed,and $sgn(\cdot)$ returns the sign (-1 or 1) of a given quantity; in this case the head difference H. C_d is the sluice gate discharge coefficient that is dependent on the design of the sluice gates [21]. Higher C_d values imply that a lower sluice gate area (A_s) might be required and thus reduce construction costs; previous studies experimentally demonstrated that values higher than unity can be achieved [22,23] through sluice gate design modifications. For regional and far-field scale coastal ocean models a sensitivity test to the parameter C_d can be found in Bray et al. [24]. Nonetheless, a value of unity is normally selected within regional scale models [9,13] and this practice has been adopted here. A sinusoidal ramp function taking the values $r(t) = \sin(\pi/2 \times (t - t_m)/t_r)$ for $t \in [t_m, t_m + t_r]$, and unity otherwise, represents the transition at the beginning of a mode where t_r is the interval expected when opening hydraulic structures and t_m the time when the current mode was triggered. Similar expressions are imposed when closing the hydraulic structures.

The flow through turbine caissons is not reliably calculated using Eq. (3) as discussed previously [9]. Instead, hill chart parametrisations are preferable while power is generated to reflect the installed turbine characteristics [25]. If followed sequentially, the equations in Table 2 can be used to calculate the flow rate and the energy generated from a bulb turbine for a given H value. This yields the tidal turbine flow rate Q_t (m^3/s):

$$Q_t(m,H,t) = \begin{cases} -r(t)\cdot \mathrm{sgn}(H)\cdot N\cdot Q_p & \text{for } m \in \{1,5\} \\ r(t)\cdot \mathrm{sgn}(H)\cdot N\cdot Q_h(H) & \text{for } m \in \{3a,3b,7a,7b\} \\ r(t)\cdot \mathrm{sgn}(H)\cdot N\cdot C_t\cdot \sqrt{2g|H|}\cdot \pi D^2/4 & \text{for } m \in \{4,8\} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where N is the number of turbines installed, Q_p (m^3/s) the pumping flow rate, Q_h (m^3/s) the flow rate according to the hill chart parametrisation of Table 2 and D (m) the turbine diameter. C_t is a non-dimensional turbine discharge coefficient that is applied to the orifice equation. It scales the flow rate based on the transition between turbine generation and sluicing according to the turbine specifications. The power P_t (MW) produced from tidal range turbines can be expressed as:

$$P_t(m,H,t) = \begin{cases} -r(t)\cdot \rho\cdot g\cdot Q_p\cdot |H|/\eta_p & \text{for } m \in \{1,5\} \\ r(t)\cdot P_h(|H|) & \text{for } m \in \{3a,3b,7a,7b\} \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where P_h (MW) is the power calculated from the sequence in Table 2 and η_p is a pumping efficiency which is a function of H [26].

2.3. Operation modelling

The simulation of the tidal power plant performance can be accomplished in several ways [9,27,28]. Essentially, the domain is split into downstream (outer) and upstream (inland) sub-domains connected at the hydraulic structure location. The downstream water levels