Renewable Energy 64 (2014) 10–25

Contents lists available at ScienceDirect

Renewable Energy

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

The effects of array configuration on the hydro-environmental impacts of tidal turbines

D. Fallon, M. Hartnett, A. Olbert, S. Nash*

College of Engineering & Informatics and The Ryan Institute for Environmental, Marine and Energy Research, National University of Ireland, Galway, Ireland

ARTICLE INFO

Article history:
Received 10 December 2012
Accepted 19 October 2013
Available online 16 November 2013

Keywords:
Tidal turbines
Array configuration
Hydro-environmental impacts
Turbine spacing
Actuator disc
Shannon Estuary

ABSTRACT

The economic viability of tidal turbines will require the deployment of multiple devices in array formations in a manner analogous to wind farms. This research investigates the effects of the configuration of a tidal turbine array, specifically the turbine spacing and capacity, on the hydro-environmental impacts of the array. The hydrodynamic regime of the Shannon Estuary, a highly energetic estuary on the west coast of Ireland, was simulated using a depth integrated 2D hydro-environmental model. The numerical model was modified to incorporate the mechanics of energy extraction using linear momentum actuator disc theory and the impacts of a multiple device array were simulated. Three different array configurations were examined with turbine spacings of 0.5, 2 and 5 rotor diameters. The model results demonstrate that flows are attenuated inside the array and accelerated around the array. Water levels are also affected with a reduction in tidal range within, and upstream of, the array and a delay in high and low tides upstream of the array. The magnitude and extent of the observed impacts are found to reduce as the density and capacity are increased and that the impacts of large-scale arrays can be acceptable if deployed using a low density spacing of 5 rotor diameters.

1. Introduction

While the only commercial-scale deployments of tidal stream turbines to date have been single devices, the next stage of progression will involve installation of multiple-device arrays (farms). Array configurations will be site specific and many factors will determine the array geometry and spacing. One such factor is the hydro-environmental impact of the array; for example, it is recognised that tidal turbines will alter ambient flow patterns due to extraction of kinetic energy. Studies based on open channel flow theory have shown that energy extraction in a simple channel driven by differences in static head can have a substantial effect upstream and downstream of the extraction site. This implies that the hydro-environmental impacts of energy extraction extend beyond the vicinity of the extraction location [1]. The one-dimensional theories presented by Garrett and Cummins [2,3] and Blanchfield et al. [4] assume that the entire flow is intercepted by the tidal stream energy converters. Garrett and Cummins [5] further developed their one-dimensional theory to incorporate energy converters occupying only a fraction of the channel cross-section, as will more likely be necessary to satisfy navigational and ecological constraints. The theoretical limit on extractable power in open flow, known as the Lanchester–Betz limit, is 16/27 (0.59) of the upstream kinetic energy flux [5], although it has been shown that this limit may be exceeded if the blockage ratio, i.e. the fraction of the channel cross-section occupied by turbines, is high. Typically, the flow speed decreases to two-thirds the upstream flow speed through the turbine and reduces further to one-third the upstream flow speed as the flow expands in the turbine wake. Garrett and Cummins [5] showed that power is lost as the slow moving water in the turbine wake merges with the fast flowing free stream downstream of a turbine in a channel. Drag on turbine support structures is also unproductive, further slowing the flow and diminishing the power potential without being associated with power generation.

There have been relatively few studies conducted on the impacts of tidal turbine arrays. Ahmadian et al. [6] modelled the energy extraction effects of a 2000 device turbine array in the Severn estuary; recorded impacts included reductions in current velocities inside the array, accelerated flows outside the array as well as consequential impacts on sediment and faecal bacteria levels. In a follow-on study which also used the Severn estuary model, Ahmadian and Falconer [7] showed that the power output

---

* Corresponding author. Tel.: +353 91 493738.
E-mail address: stephen.nash@nuigalway.ie (S. Nash).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.10.035

and hydro-environmental impacts of a turbine array are sensitive to the shape of the array. Myers and Bahaj [8] carried out experimental work which quantified the flow field around a two-row tidal array and ascertained an optimal lateral turbine spacing where, under certain conditions flow can be increased between a pair of actuator disks. The optimal spacing for energy harvesting was shown to be an inner disk separation of 1.5 rotor diameters in a water depth of 3 rotor diameters. For this spacing, the accelerated flow contained 22% more kinetic energy than the flow upstream of the energy converters without having a negative effect on the two rotor disks. Model studies investigating the impacts of tidal energy convertor arrays on sediment dynamics have shown that arrays sited near headland sand banks could result in significant changes to their morphology [9] and arrays sited in regions of strong tidal asymmetry can have a much more pronounced effect on sediment dynamics than energy extracted from regions of tidal symmetry [10]. Finally, in a one-dimensional modelling study, Polagye and Malte [11] quantified changes to tides, transport, frictional power dissipation, and kinetic power density as a result of tidal energy extraction in four prototypical channel networks.

The objective of the present research was to investigate the effect of configuration on the hydro-environmental impacts of tidal turbine arrays. The tidal regime of the Shannon Estuary, a highly energetic estuary on the west coast of Ireland with significant potential for tidal current energy extraction, was simulated using a depth-integrated, 2D, hydro-environmental model. The numerical model was modified to simulate the mechanics of energy extraction and its effects on the tidal regime. A multiple device array was simulated and three different array configurations were examined using turbine spacings of 0.5, 2 and 5 times the rotor diameter. The numerical model details are discussed in Section 2 which explains the governing equations and the turbine representation within the model. Section 3 outlines the model application to the Shannon Estuary, including a description of the model details and a brief explanation of the model scenarios. The results are presented in Section 4 and comprise three sections describing: 1) tidal flows, 2) tidal elevations and 3) energy fluxes. Finally, discussion and conclusions are presented in Sections 5 and 6 which highlight the hydro-environmental impacts associated with tidal turbines and their sensitivity to array configuration.

2. Model details

The numerical model used for this research was an amended version of DIVAST (Depth Integrated Velocities and Solute Transport), a two-dimensional, depth integrated, finite difference model. The model is capable of simulating hydrodynamics, solute transport and water quality in reasonably shallow estuarine and coastal water bodies [12–14].

2.1. Governing equations

The hydrodynamic module is based on the solution of the Navier–Stokes equations and takes account of the effects of local and advective accelerations, earth's rotation, barotropic pressure gradients, wind action, bed resistance and turbulence. The depth integrated continuity and x-direction momentum equations (similarly for y-direction) can be expressed in the following form:

Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \tag{1}$$

x-Direction momentum equation:

$$\frac{\partial q_x}{\partial t} + \beta\left[\frac{\partial U q_x}{\partial x} + \frac{\partial U q_y}{\partial y}\right] = f q_y - gH\frac{\partial \zeta}{\partial x} + \frac{\tau_{xw}}{\rho} - \frac{\tau_{xb}}{\rho} + 2\frac{\partial}{\partial x}\left[\varepsilon H \frac{\partial U}{\partial x}\right] + \frac{\partial}{\partial y}\left[\varepsilon H\left[\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right]\right] \tag{2}$$

where t = time; ζ = water surface elevation above mean water; q_x, q_y = depth averaged volumetric flux components in the x, y directions; U, V = depth averaged velocity components in the x, y directions; β = momentum correction factor; f = Coriolis parameter; g = gravitational acceleration; ρ = fluid density; τ_{xw}, τ_{yw} = surface wind shear stress components in the x, y directions; τ_{xb}, τ_{yb} = bed shear stress components in the x, y directions and ε = depth averaged eddy viscosity. Falconer [15] describes in detail the momentum correction factor, the wind and bed shear stress components and the depth averaged eddy viscosity.

The model employs an implicit finite difference scheme based upon the Alternating Direction Implicit technique to solve the governing differential equations. This technique divides each time step into two half-time steps, enabling a two-dimensional implicit scheme to be applied; however, only one dimension is considered implicitly for each half-time step. The major advantage with this approach is that it eradicates the requirement for solving a complete two-dimensional matrix and reduces the computational cost. The model carries out computations on a uniform rectilinear grid with equivalent grid spacings in the x- and y-planes.

2.2. Turbine representation

Representation of horizontal-axis tidal turbines in the numerical model was based on linear momentum actuator disc theory (LMADT) [16] which considers a stream tube enclosing a turbine rotor in an open channel. The rotor is modelled as an actuator disk which takes momentum from the flow. Fig. 1 illustrates five stations: (1) far upstream of the turbine, (2) immediately upstream of the turbine, (3) immediately downstream of the turbine, (4) the region where the slower moving flow from the turbine's wake merges with the free stream fluid from the by-pass flow and (5) adequately far enough downstream from the turbine that the pressure regains uniformity. The section of flow passing through the turbine is denoted by subscript t and the bypass flow is denoted by subscript b.

The flow passing through the turbine will experience a reduction in velocity across the rotor plane (1–3). Immediately downstream of the turbine (3–4), the turbine flow is moving at a slower velocity than the bypass flow diverted around the rotor and must expand to satisfy conservation of momentum. This action generates the turbine's wake (cone-shaped region downstream of the rotor) which also contains turbulent mixing. At a sufficient distance far

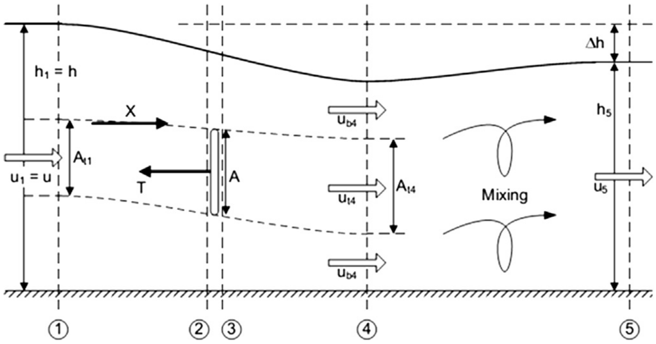

Fig. 1. Linear momentum actuator disc theory in open channel flow [13].