Renewable Energy 127 (2018) 168–181

Contents lists available at ScienceDirect

Renewable Energy

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

Experimental study of wake characteristics in tidal turbine arrays

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ARTICLE INFO

Article history:
Received 9 August 2017
Received in revised form
1 February 2018
Accepted 15 April 2018
Available online 18 April 2018

Keywords:
Tidal turbine arrays
Wake measurements
Turbulence intensity
Particle image velocimetry (PIV)

ABSTRACT

For the successful deployment of large scale tidal turbine arrays occupying a large part of tidal channels, understanding the effects of wake interaction in densely spaced arrays is of importance. A comprehensive set of experiments has been conducted with scaled tidal turbines to investigate the resulting wake characteristics in a number of different staggered array configurations with up to four turbines on a designated support frame. Wake velocity deficits and turbulence intensities at a number of locations within and downstream of the array are presented and in addition the flow field recordings from Particle Image Velocimetry (PIV) measurements are presented for visual investigation of the resulting wake field and wake characteristics along the array centre line. The experiments show that lateral and longitudinal spacing variations of the individual devices vary the resulting flow field downstream of the array section significantly. Lateral spacing can be optimised to result in beneficial flow effects that accelerate the downstream wake recovery. Very close spacing however leads to significantly reduced velocity recovery. Longitudinal spacing shows less significant influence, especially for configurations with wide lateral distances. Differences in wake velocity deficit of up to 10% have been identified and suggest array wake recovery in and downstream of staggered sections, in areas of lower ambient turbulence levels, to be more significantly influenced by the lateral spacing especially towards the front rows of the array. With every additional array section the increasing turbulence intensity within the array is anticipated to reduce this effect.

1. Introduction

1.1. Marine & renewable energy

Continuing efforts are being made to achieve the challenging 2020 renewable energy targets by providing a diverse, low-carbon and secure energy mix [1]. Within the field of renewable electricity, the oceans as a direct source of sustainable energy, predominantly through conversion of kinetic energy in waves and tidal currents have gained considerable interest for the generation of electricity over the past and have an estimated combined potential of providing up to 20% of the UK's electricity demand [2].

Electricity generation from tidal currents draws upon similarities with the wind energy sector, however the challenges posed to make this electricity economically viable are more complex due to operating in highly temporarily and spatially varying flows and across a large part of the current boundary layer. Additionally, the complex bathymetry and influences of waves and sediment transport affect the performance and wake evolution of tidal turbines. Tidal stream energy has the advantages of high energy density, being practically out of sight and being the most reliable and long term predictable renewable energy source available.

Currently, the industry is preparing to move from single demonstrator projects to first generation commercial arrays with installation and first stage operation currently in progress at the MeyGen project site (MeyGen confirmed first power of single device in 2016 [3–5] and has since installed 4 turbines, generating electricity [6]). Further, and accelerated development of large scale tidal turbine arrays is anticipated beyond 2020 [1].

Due to the high cost involved and complexity of operating in harsh environments, improved understanding and prediction of likely energy yields is needed which requires comprehensive studies of the complex flow interactions and the effect on tidal turbines when arranged in large arrays. Experimental studies that investigate the flow characteristics within model scale tidal turbine arrays are a vital step towards validation and application of numerical models for further investigation of array deployment at reduced cost and risks.

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https://doi.org/10.1016/j.renene.2018.04.053
0960-1481/

1.2. Problem and inadequacies of current status

The design and performance of individual devices has been investigated using a range of numerical simulations, some of which in combination with experiments [7], and experimental studies ranging from small actuator disks [8] through scaled tidal turbines to large scale prototypes deployed in open water [9]. The assessment of tidal turbines operating in array has largely been done numerically using simplified Blade Element Momentum theory (BEMT) through fully resolved three dimensional computational fluid dynamics (CFD) to large scale hydro-environmental modelling [10–13] examining the performance and energy yields of single devices and proposed arrays without experiments to support the outcome of numerical calculations. Theoretical models have shown that power generation of turbine operating in tidal channel is improved by increasing the blockage ratio [14] and where it's practically infeasible to occupy the entire width of a channel, the energy produced reduces to 1/3 of the tidal fence for turbines occupying a large fraction of the channel cross-section and to 2/3 of that of a tidal fence across the entire cross section for turbines covering a small section of the channel cross sections. Extending this to tidal turbine arrays has shown that with increasing local blockage efficiency is increased up to a level where total array efficiency is reduced due to array scale chocking effects reducing the flow through the entire array [15]. Investigations of centred and staggered arrays using theoretical linear momentum actuator disk theory [16] showed that for multi row arrays the device spacing within each row is a function of the number of rows, reducing the optimum blockage from 0.4 for one fence to 0.12 for two fences with a distance downstream between both of the order of the fence width. With additional rows this trend continues, thus recommendations for large spacing within each row to maximize power per turbine similar to offshore wind farms are made.

Near wake characterisation up to 10 diameter (D) downstream of a single turbine by experiment has been presented previously with focus on ambient turbulence [17] and device generated turbulence [18] affecting the wake structure. Detailed accounts have been taken of the evolution of wake velocity and turbulence at a number of positions throughout the wakes, showing the recovery towards ambient conditions at a number of different operating conditions and highlighting the accelerated wake recovery with increased ambient turbulence levels. Three dimensional volumetric flow field visualisation of the wake of a miniature tidal turbine have been presented by Chamorro et al. [19] up to 5D behind the turbine. The small-scale wake measurements revealed detailed information about dynamic wake features such as the wake expansion being proportional to one-third-power law. The dynamics interaction of vortices and their breakdown to the loss of wake stability occurring within 1D downstream of the turbine.

Recent experimental studies that investigated wake characteristics and interaction effects of multiple tidal turbines operating in in-line configuration and first generation arrays are still limited in number and complexity of formations tested [20–23] and focused mainly on the interaction effects for different downstream spacings. Comparison of wake characteristics of a single device and a second device operating within the wake of an upstream device [20] showed similar behaviour for the downstream wake as compared to the high ambient turbulence case for a single turbine. Performance of second row devices with spacings between 2D and 12D in low ambient turbulence environments was about half of the upstream turbine. For higher turbulent intensities, the performance was within 10% for downstream placing of 6D and more. Flow measurements in these experiments were primarily done using pointwise Acoustic Doppler Velocimetry (ADV) or Laser Doppler velocimetry (LDV) measurements across the wake region for wake characterisation and performance evaluation.

Particle Image Velocimetry (PIV) has so far only been applied to a very limited number of tidal turbine studies and their wake characterisation. While Shi, Atlar and Norman [24] investigated the blade scale flow using PIV, wake characterisation using PIV measurements by Good, Hamill, Whittaker and Robinson [25] was shown to investigate the flow field around a tidal turbine structure in an experimental test channel to account for the change in flow field due to the support structure and a rotor spinning freely. Flow acceleration on top and bottom tip of the device have been observed and the vertical profiles show the characteristic transition from hat shaped to bell shaped profile between 0.5D and 1D. No power take-off was simulated and measurements extended downstream only 1.5D.

Myers and Bahaj [21] used up to three actuator disks to investigate wake interaction with varying lateral separation between two disks in a single row array, and a two-row array with a third actuator disk being located 3D downstream of the first row. Optimum lateral spacing was shown to increase flow velocity between adjacent disks with 1.5D spacing, where smaller spacing showed combined wakes of each individual disk and increased thrust coefficients. By placing a third disk in the accelerated jet between the two upstream disks, the near wake deficit of the first row turbines was reduced as these were diverted around the downstream disk. The combined wakes further downstream of the array showed increased width and higher centre line velocity deficits due to reduced mixing with ambient flow and penetrating towards the wake centreline. No increase in thrust of the upstream disks was recorded when placing a third disk downstream and the thrust coefficient of the downstream disk is equivalent to the upstream disk with $C_T \cong 0.92$, using the inflow velocity at the position of the disk in its absence.

Previous experiments by Myers and Bahaj [26] investigated the effects of boundary proximity by altering the vertical position of actuator disks in an experimental flume and have shown increased wake velocity deficit with increasing proximity to the sea bed. Tests with increased seabed roughness representing more accurately the realistic ambient turbulence levels are used to investigate accelerated wake re-energisation and have shown merging of the disk and seabed wake for close proximity to the seabed thus extending the wake further downstream. This is an important consideration for the design of support structure and the authors showed that increased turbulence intensities alone, especially at low current velocities may not translate into accelerated wake recovery as expected.

A number of model scale arrays has been tested in a wide flume [22] to investigate changes in wake structure when arranging turbines in array. Longitudinal, lateral and vertical velocity profiles and turbulence intensities are presented for several arrangements of multiple turbines located in a single row. For lateral separation of 2D and less, wake merging between adjacent wakes was observed resulting in nearly constant velocity deficit across the wake width by 8D downstream. For these configurations, thinner wake shapes and faster wake recovery are seen in areas between wakes due to increased turbulence levels. The effect of multiple rows on the wake profiles at two distances downstream of the group of rotors and thrust coefficients for individual rotors has been presented by Olczak, Stallard, Feng and Stansby [23] showing reducing thrust coefficients for each subsequent row of turbines and in comparison with RANS-BEMT simulations decreasing accuracy of the predicted values with each additional row downstream. especially for turbines in the centre of the array. The wake velocity deficit was largest for the outer turbines and reduced, but showed individual peaks for each rotor within 2D and 4D of the last row.

To the author's knowledge, this study is the first experimental