The influence of tidal turbine arrangement on the wake interaction in shallow water

G E Suhri, A Rahman*, L Dass and K Rajendran

Mechanical Engineering Program, Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia.

*Email: anasrahman@unimap.edu.my

Abstract. The arrangement of tidal turbines in the tidal farm is known to be complicated due to the resistance to the tidal flow which causes the flow to be channeled around the individual devices. To successfully implement the tidal turbine, the wake interaction between the device and its implication needs to be fully understood. Typically, the wake interaction in the array depends on the arrangement and spacing between the device in the array. In this study, a numerical analysis is conducted through the use of Computational Fluid Dynamic (CFD) approach to investigate the influence of the array setup in shallow water application and to propose a suitable array layout for possible application in Malaysia. The numerical analysis is carried out with 2 combination sets of lateral and longitudinal spacing covering 15 turbines in staggered and squared array layout. Hypothetical ‘actuator’ disk and ‘actuator’ cylinder model are used to represent the Horizontal axis turbine (HATT) and Vertical axis turbine (VATT) respectively. The results showed that the VATT model has faster wake recovery and obeys the definition of the far wake. Staggered arrays with bigger spacing are preferable for application in shallow water due to the low probability of wake merging between the rows.

1. Introduction

The negative impact contributed by the usage of fossil fuel to generate electricity has led to changes in technologies. To ensure a clean environment the use of renewable energy has been taken as an alternative to lessen the dependency on fossil fuels usage [1]. Among many available renewable energy resources, tidal current energy has captured the most interest due to its simplicity and cost-effectiveness. Tidal current energy has demonstrated considerable potential for generating electricity in the coastal area due to the abundance of energy resources in the ocean as tidal energy is always predictable and available each year [2]. The energy collected from high-velocity tidal flows by turbines is predicted to be able to contribute significantly to provide electricity for the community. To transform the kinetic energy of tidal currents into electrical power, various tidal stream turbines design has been developed. The tidal turbine energy system is an adaptation from the wind turbine system and is often considered to be analogous in regards to how the energy is extracted from a moving fluid [3]. Despite sharing some similarities with the wind energy extraction, to make the tidal turbine energy system to be commercially visible are more complex as it is operating in condition with temporarily and spatially varying flows, complicated bathymetry, and dealing with the effects of waves and sediment transport. Also, only part of the existing expertise and methods of the wind energy system can be implemented and transferred to a tidal turbine energy system since operating conditions of the wind energy system present significant specialties [4]. On the other hand, tidal
stream energy offers the benefits of having a greater energy density, being virtually invisible, and providing the most consistent and lasting predictable renewable energy source accessible making it widely acknowledged and captured many interests when compared to other marine renewable energy.

The tidal turbine performance is highly influenced by the array layouts. In an array, the presence of wake shadowing and wake merging between the devices in rows in the array may give negative feedback to the efficiency of the farm [5]. This phenomenon is caused by the recovery of momentum after the first row of the turbine [6] thus leading to reduction of power generation by the downstream devices and is harmful to the whole farm [7]. This must be avoided by taking the spacing, arrangement, and number of devices into consideration in developing the tidal turbine array. To identify the ideal layout of a turbine array, several studies have been conducted to analyse the effects of array scale and configuration in terms of device spacing and arrangement on the wake interaction on the tidal farm.

Mycek et al. [8] conducted a study with two inline turbines under different spacing and environmental conditions. Because of faster wake recovery in highly turbulent conditions, they discover that the downstream turbine is less influenced by the upper stream turbine. On the other hand, Stallard et al. [4] found that increasing the lateral spacing between the device in a row will increase the distance where the individual wake will merge. Meanwhile, Harrison et al [9] examined the wake interaction of tidal farms with 5 devices and row organised in a stream-wise manner. According to their study, the power on the second row was the lowest. The turbine in the third row onwards showed better performance in terms of power generated due to high wake recovery inside the array. Nonetheless, most of the research are focused on the small array and for deep-water application. Compared to the European coastline, current velocities on Malaysia’s coastline are relatively low with velocities ranging from 0.8 m/s to 1.2 m/s with a water depth of 60 m. Studies regarding large array and for shallow water application are limited hence one of the reasons why this study is conducted. This study is performed by looking at several sets of turbines spacing and array layouts to investigate the influence of array setup and to propose a suitable array layout for application in shallow water.

2. Methodology

2.1. Dimension specification of the model

Two types of models have been used as the turbine representative. Hypothetical ‘actuator’ disc and ‘actuator’ cylinder were used to represent the horizontal axis tidal turbine (HATT) and vertical axis tidal turbine (VATT) respectively. Meanwhile, a rectangular shape domain was employed to illustrate an open channel. The geometric and parameters specified for the model and domain are adopted from previous studies by Hoe [10] and Bakri [11], in which their parameters are illustrated in Figure 1.

![Figure 1. Dimension specification of model and domain for the study: a) ‘Actuator’ cylinder b) ‘Actuator’ disk and c) Domain](image-url)
Next, two sets of spacing are established and applied in arranging 15 turbines in both staggered and squared manner. In staggered array, the turbine is arranged in formation such as rows of 3 and 2 turbines are positioned alternating with each other. Meanwhile, in squared array rows of 3 turbines are located aligned with each other. Besides that, the two sets of spacing cover one set of small distance separation and one set of longer distance separation. These sets are used to identify the wake interaction due to the turbine separation. The dimension specification of the separation is shown in Table 1.

Table 1. The lateral and longitudinal spacing used between the turbine in the array.

| Parameter       | Lateral spacing (m) | Longitudinal spacing (m) |
|-----------------|---------------------|--------------------------|
| Set 1           | 1.5D                | 3.5D                     |
| Set 2           | 3.0D                | 7.0D                     |

2.2. Meshing procedure

In any engineering simulation, a meshing procedure is necessary to break down the complicated structure into simpler elements that can be applied as discreet local approximations of the bigger domain. In this study localized meshing procedure is implemented to get more refined results. The localized meshing was applied at the domain’s body, the model’s face, and edges with meshing parameters as simplified in Table 2.

Table 2. Localized meshing parameter applied to the domain and model.

| Location            | Element size/behaviour |
|---------------------|-------------------------|
| Body of the domain  | 2.0 m                   |
| Faces of the model  | 0.25 m                  |
| Edges of the model  | 0.2 m                   |
| Meshing behavior    | Soft                    |

2.3. Simulation procedure

The simulation was conducted by defining the following parameters - seawater was defined as the material with density and dynamic viscosity of 1023 kg/m³ and 0.00093 N.s/m² respectively. No-slip condition is applied at the control volume boundary where the inlet, outlet, and the domain’s top wall plane were defined as the boundary condition with specification as reported in Table 3. The value for all the parameters on Table 3 are set following previous study by Bakri for validation purpose.

Table 3. Parameters specification for boundary condition setup.

| Parameter                | Specification         |
|--------------------------|-----------------------|
| Velocity magnitude       | 1 m/s                 |
| Turbulent intensity      | 5 %                   |
| Hydraulic diameter       | 0.1 m                 |
| Shear condition          | No-slip condition      |

The three-dimensional numerical calculation was performed using the Reynolds-Average Navier Stokes equation (RANS) with the k-epsilon model on Ansys. The equation is solved sequentially by using a pressure-based solver, SIMPLE algorithm. The simulation was completed with a total of 300 iterations.
3. Simulation results and analysis

3.1. Wake behavior on squared and staggered array for HATT and VATT model

Figure 2 shows the velocity contour of the squared array and staggered for the HATT and VATT simulations. The velocity contour shows that both models accurately replicated the characteristics of the wake behavior. High velocity is developed in front of the first-row turbine surface. The flow then experienced velocity reduction after passing through the next rows of the turbine. This low-velocity region established behind the turbines is the result of energy loss when the flow is hitting the turbine surfaces. On the other side, it is observed that the velocity behind each row of the turbine for the VATT model is higher compared to the HATT model as represented by the yellow and blue region in the contour. This shows that VATT model simulation experienced lesser velocity reduction compared to HATT model simulation.

By analyzing the velocity contour region, also notice that the VATT model recovered faster than the HATT model. There is more turbulence mixing in the HATT model which is represented by the green color region. This behavior is correlated with the wake nature in which turbulent energy will be produced due to the velocity gradient in the shear zone isolating the inner core of the wake from ambient flow [12]. Also from Figure 2, it is observed that the individual wake of each turbine is more significant in staggered array arrangement compared to the squared arrangement. In the staggered arrangement, the merging of flow is less likely to occur due to its alternate arrangement as the flows are not interrupted by the downstream turbine.
Figure 2. Velocity contour results for HATT and VATT model arranged in the staggered and
squared array: (a) VATT model in squared array (b) VATT model in staggered array, (c) HATT
model in the squared array, (d) HATT model in a staggered array.

3.2. Wake behaviour based on comparison on normalised velocity plot for HATT and VATT model.

Figure 3 displays the comparison of the normalized velocity of the staggered and square for
VATT and HATT model simulations for this study. On the graph the y-axis (y/D) represents the depth
(y) per diameter (D) and the x-axis (U/Uo) represent the locality velocity (U) per stream velocity
(Uo). As presented in Figure 3, at 9D downstream distance (where D is the device diameter), the
normalized velocity line of the VATT model for both array layouts is located to the right of the graph.
The VATT model in Figure 3(b) also shows the model both in the staggered and squared array are
seemed to have faster recovery than the HATT model due to a higher value of the normalised velocity
at the centreline than HATT model in Figure 3(a). This is due to the shape of the model itself. The flat
disc geometry of HATT turbines has caused the velocity of the fluid to disperse at the side of the
model and causing the fluid to carry higher turbulent kinetic energy when it is passing through the
turbine.

Figure 3. Comparison of the normalized velocity of spacing (1.5D ×3.5D) and spacing (3.0D ×7.0D)
in staggered and squared array at 9D downstream for (a) HATT model (b) VATT model.

Comparison in terms of spacing and layout on the other hand presented a result such as for the HATT
model, the wake recovery for the model in both arrangement and spacing sets are nearly the same.
The normalised velocity falls within 0.1 m/s – 0.2 m/s. However, detailed observation has been made
and the results show that squared array with spacing set of 3.0D ×7.0D (i.e. latitudinal × longitudinal
distance) shows the fastest recovery followed by the model in squared array with 1.5D ×3.5D. The
HATT model in the staggered array for both sets of spacing has a slightly slower recovery compared
to the squared array. This is because the turbulent intensity for the HATT model arranged in a
staggered array is noticed to be higher than the HATT model arranged in squared which has caused
the flow to become slower.

However, the opposite trend is observed for the VATT model simulation. At 9D downstream, the
VATT model in staggered array with a spacing of 3.0D ×7.0D shows the fastest recovery among
others. It then followed by the VATT model in a staggered array with a spacing of 1.5D ×3.5D. This
is because the wake merging is less likely to occur between the flow from the upper turbine and the
downstream turbine which was affected by the slower velocity downstream due to the staggering manners.

By considering the normalized velocity pattern of the HATT and VATT models, it can be seen that the VATT model works better than the HATT model. Additionally, the VATT model is also best installed in staggered layouts. Meanwhile, from the results HATT seems best to be installed in the squared array. However, the potential of wake merging with downstream turbine is higher in the squared array than the staggering array due to the linear arrangement of the devices, and this needs to be considered. The VATT model also obeys the far wake region definition which is one of the most preferable conditions for shallow water application. The faster the wake recovery reduces the possibility for the wake to merge at the downstream region. If the merging of wake happens, the upstream flow (after passing upstream devices/rows) will carry less kinetic energy when reaching the subsequent/downstream rows. Therefore, this will reduce the overall performance of the array for optimal energy extraction.

4. Conclusion
Based on results presented, it can be concluded that:

• The performance of VATT model for both staggered and squared array layout surpasses the HATT model in term of wake recovery. Hence, VATT is more suitable to be installed for shallow water application based on the simulation input.

• The model with a staggered setup shows better performance compared to the squared array due to the lesser possibility of wake merging. VATT model that is arranged in a staggered layout with bigger spacing provides the best possible configuration for potential tidal farm.

• Nonetheless, optimal spacing needs to be studied in detail as it is highly dependent on the deployment locations.

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