Arrangement optimization of three tidal turbines considering efficiency and productivity

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Abstract— **Tidal current power is one of the promising renewable energy resources with high energy density, reliable energy supply and predictability of energy production. Recently many countries, especially the U.K., announced and launched a number of tidal farm projects. For these projects to be successfully developed, each project should maximize its efficiency and productivity. The optimization of the tidal turbine arrangement is one of the key issues to maximize the economic feasibility of tidal farms. This study introduces the diagonal arrangement of three tidal turbines and investigates the performance of these tidal turbines in various arrangements using 3D CFD (Computational Fluid Dynamics) analysis. A tidal turbine of which maximum power coefficient is 47.5% was used to simulate the diagonal arrangement of three turbines. The results show that the diagonal arrangement increases the rear turbine efficiency by 3% and decreases the front turbine efficiency by 0.5%.**

***Keywords*— Tidal current power, Horizontal axis turbine, Arrangement optimization, Diagonal arrangement, CFD (Computational Fluid Dynamics)**

I. INTRODUCTION

Tidal current power is one of the promising renewable energy resources with high energy density, reliable energy supply and predictability of energy production. These characteristics are very significant for grid managements. For these regions, many companies and research groups have developed tidal current devices considering operating these devices in promising regions with high tidal current speed.

Recently many tidal current farm projects are released and launched in European countries especially UK. Optimized arrangement of the tidal current devices is one of the key issues for tidal current power farm development. Obviously, optimization of arrangement would increase the efficiency and generated power of a tidal current power farm. Therefore there are many studies that have conducted experiment or numerical simulation to investigate the relation between arrangement and turbine efficiency [1-8].

In this study, diagonal arrangement of three tidal current turbines was investigated using CFD analysis. First of all a turbine was designed and validated by CFD performance analysis. The turbine diameter is 20 m and rated power assumed 1 MW at 2.5 m/s with tip speed ratio of 5. The efficiency is 47.5%. Various distance of diagonal arrangement were simulated and each case was compared with turbine efficiency and generated power per unit area. Lateral distance is 3D and 4D and downstream distance is 1.5D, 2D and 2.5D.

II. TURBINE DESIGN

A. *Design criteria*

Blade element momentum theory (BEMT) was used to design the turbine. The theory was consists of momentum theory and blade element theory. These two theories respectively set up the equations of the moment and the thrust acting on a blade by flow passing the blade. By taking the expressions for the moment and thrust derived in both theories, the equations of the axial and tangential flow induction factors and the chord-length can be derived as shown in eqs. (1), (2) and (3).

$$a = \frac{1}{\frac{4sin^2\emptyset}{\sigma C_n} + 1} \tag{1}$$

$$a' = \frac{1}{\frac{4sin\emptyset cos\emptyset}{\sigma C_t} - 1} \tag{2}$$

$$C(r) = \frac{8\pi r\lambda\mu a' sin^2\emptyset}{n(1-a)C_t} \tag{3}$$

The momentum theory assumes the efficiency higher than the actual turbine. Ludwig Prandtl presented the tip loss factor in order to correct this difference. Eq. (4) is the modified tip loss factor to make easier to use in practical BEM computations.

$$F = \frac{2}{\pi} cos^{-1}[\exp\left(-\frac{n(R-r)}{2rsin\emptyset}\right)] \tag{4}$$

In-house code was built Based on these equations and used to design a tidal current turbine with the parameters shown in Table 1. The result shows in Fig. 1.

TABLE I
DESIGN PARAMETERS

Design parameters		Values
diameter		20 m
rated power		1 MW
rated current speed		2.5 m/s
number of blades		3
tip speed ratio		5
angle of attack	S818	7
	S830	6
	S832	6
lift coefficient	S818	1.195
	S830	1.256
	S832	1.176
drag coefficient	S818	0.018
	S830	0.017
	S832	0.015

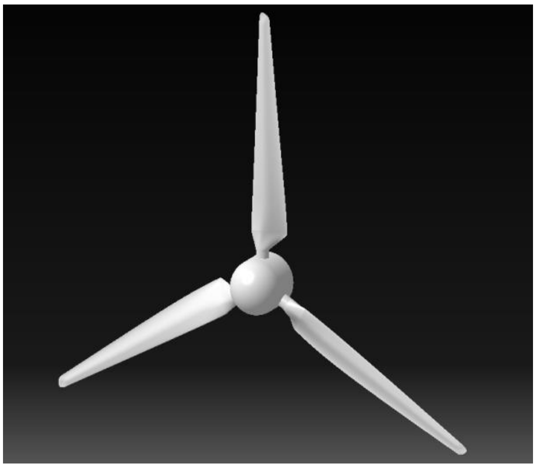

Fig. 1 Solid model of the tidal turbine

B. Performance

The performance of the turbine was validated using the ANSYS CFX commercial CFD code. The fluid domain of a blade was generated and uniform velocity inlet, averaged static pressure outlet and rotational periodic are applied as the boundary condition. Shear stress transport (SST) turbulence model was used and the results are shown in Fig. 2 and 3.

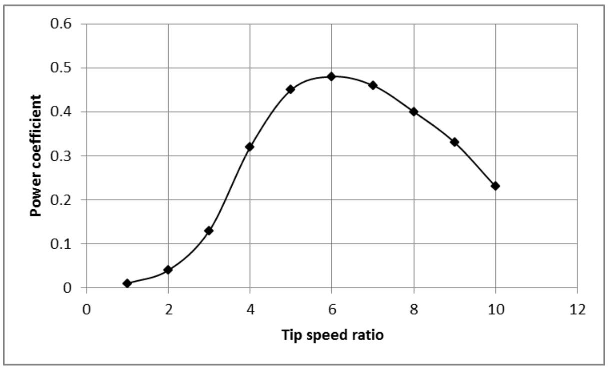

Fig. 2 Power coefficient

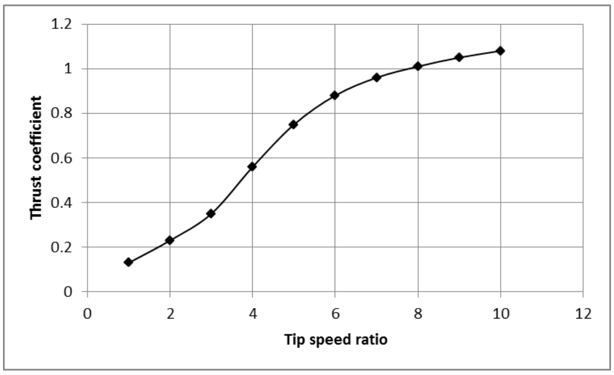

Fig. 3 Thrust coefficient

III. DIAGONAL ARRANGEMENT

A. Calculation condition

There are many studies that tidal current turbine arrangement should be diagonal to be efficient. Flow speed between two front turbines is increased and the performance of the rear turbine increased. Meyer et al. shows that the optimum lateral distance is 2D and optimum downstream distance is 4D. However, this result was derived from experiment using porous disk that could not represent the rotating flow in wake flow.

Therefore in this study, the diagonal arrangement was simulated using different arrangement in Table 2. Lateral distance (a) was 1.5D, 2D and 2.5D and downstream distance (b) was 3D and 4D. Fig. 4 shows the computational domain and Figs. 5 and 6 shows the grid system.

TABLE III
LATERAL AND DOWNSTREAM DISTANCE

Case	Lateral distance	Longitudinal distance
1.5-3	1.5D	3D
2-3	2D	3D
2.5-3	2.5D	3D
1.5-4	1.5D	4D
2-4	2D	4D
2.5-4	2.5D	4D

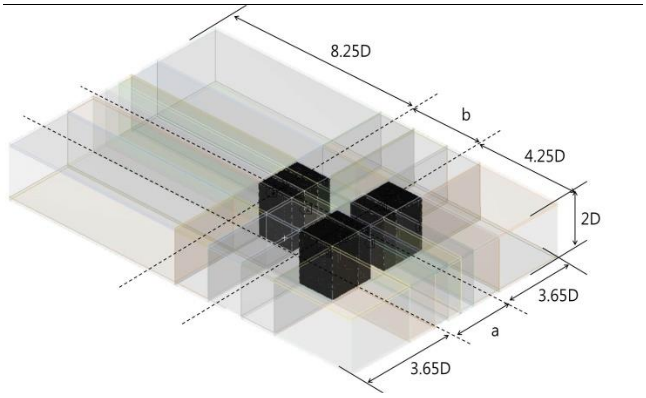

Fig. 4 Computational domain

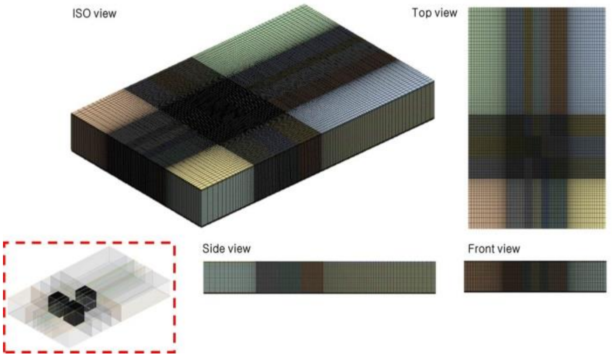

Fig. 5 Gird system of whole domain

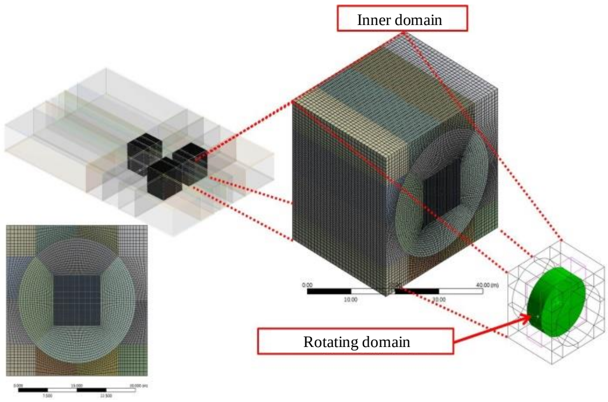

Fig. 6 Gird system of inner domain

Table 3 shows the analysis conditions. Inlet velocity was rated current speed of 2.5 m/s and outlet was averaged static pressure. The bottom and turbines were defined as non-slip wall. MRF method and k-ω SST turbulence model was applied.

TABLE IIIII
LATERAL AND LONGITUDINAL DISTANCE

Description	**Analysis condition**
Analysis type	Steady state
Inlet	Normal speed (2.5 m/s)
outlet	Averaged static pressure (1 atm)
Turbine and bottom	Non-slip wall
Interface area	GGI with frozen rotor
Angular velocity	MRF method
Turbulence model	k-ω SST (Shear Stress Transport)

B. Results

The efficiency of an arrangement of turbines can be estimated using averaged performance of a set of turbines. Diagonal arrangement can be divided into a set of a front turbine and a rear turbine.

Table 4 shows the efficiency of each turbine. The results show that when the longitudinal distance is 3D, the front turbine efficiency is not affected by the lateral spacing and rear turbine efficiency is lower with larger lateral distance. The front turbine efficiency is slightly increased and rear turbine efficiency is slightly decreased when Longitudinal distance increase from 3D to 4D. Front turbine efficiency is changed by less than 0.2% and rear turbine efficiency is changed by 0.5%.

Compared to the single turbine performance, front turbine efficiency is decreased about 0.5% and rear turbine efficiency is increased about 3%. The efficiency loss of front turbine is due to the influence of rear turbine's blockage effect and increasing of rear turbines performance is the increased flow speed between two front turbines.

When it comes to averaged turbine efficiency, Longitudinal distance of 3D is efficient than 4D cases. This means that the decreasing efficiency of two front turbines more affect to the generated power of a set of array than the increasing efficiency of a rear turbine when Longitudinal distance is increased from 3D to 4D.

TABLE IV
EFFICIENCY OF EACH TURBINE

Case	**Front left turbine efficiency (%)**	**Front right turbine efficiency (%)**	**Rear turbine efficiency (%)**	**Average turbine efficiency (%)**
1.5-3	46.96	46.99	50.60	48.18
2-3	46.97	47.00	50.59	48.19
2.5-3	46.96	46.99	50.53	48.16
1.5-4	47.11	47.14	50.10	48.12
2-4	47.09	47.11	50.19	48.13
2.5-4	47.05	47.07	50.16	48.09

There are 0.01% differences in case 1.5-3 and case 2-3. This is not enough to decide the optimum arrangement for tidal current array and therefore another factor should be considered to optimize the arrangement.

There is limited number of locations in the world ocean which have enough tidal energy density to be considered for energy extraction. Power per unit area is one of criteria for efficiency of space utilization and in the tidal current turbine arrangement; this can be calculated by dividing generated power of a set of turbines by occupied area of a set of turbines.

Table 5 shows that the total turbine power and turbine power per unit area of a diagonal set. Occupied area was calculated considering lateral distance (a) and assuming downstream distance (c) of 10D as shown in eq. (5).

$$A_{occupied} = \frac{a+1}{2} \times 10 \times D^2 \qquad (5)$$

Although case 2-3 generates power more than other cases, case 1.5-3 is most efficient arrangement with small occupied area and 1.5-4 is second effective arrangement among these cases. Longitudinal distance should be optimized considering only turbine efficiency because it is not affected to calculation of occupied area. On the other hand, latitudinal distance is used to calculate occupied area with downstream distance. Therefore latitudinal distance should be small unless it affect to the turbine efficiency. Downstream distance should be validated by experiment and CFD to secure that the wake flow velocity recovered 100% not to decrease the rear array's efficiency.

TABLE V
LATERAL AND LONGITUDINAL DISTANCE

Case	**Total turbine power (W)**	**Occupied area (m^2)**	**Turbine power per unit area (W/m^2)**
1.5-3	3,636,488	15000	242.4
2-3	3,636,889	18000	202.0
2.5-3	3,634,898	21000	173.1
1.5-4	3,631,355	15000	242.1
2-4	3,632,564	18000	201.8
2.5-4	3,629,800	21000	172.8

IV. CONCLUSIONS

Arrangement of tidal current devices is one of the most important factors that affect directly to the efficiency of tidal current devices and generated power of tidal current farm. Many studies were conducted to investigate the wake characteristics of tidal current turbine and optimize the arrangement of tidal current arrays. Although most of these researches recommend the diagonal arrangement, the optimum arrangement is not established.

In this study, a tidal current turbine was designed and used to simulate the diagonal arrangement of three turbines. The results show that this diagonal arrangement increases the rear turbine efficiency about 3% and decreases rear turbine efficiency about 0.5%. Averaged efficiency of a set of three turbines is highest at case 2-3 where lateral distance is 2D and longitudinal distance is 3D. Front turbine efficiency is increased and rear turbine efficiency is decreased when the longitudinal distance is increased from 3D to 4D.

However these differences of turbine performance are less than 0.2% at front turbine and 0.5% at rear turbine. Therefore to determine the efficiency of tidal current farm by arrangement of tidal current turbines, turbine power per unit area of each case was compared. Although case 2-3 generates power more than other cases, case 1.5-3 is most efficient arrangement and 1.5-4 is second effective arrangement among these cases with smallest occupied area. This shows that when the arrangement is not affect the turbine performance, small occupied area is recommendable.

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