Hydrodynamic Performance Analysis of the Turbine of 2×100kW Tidal Current Energy Generation Device Based on Tidal Bladed Software

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Abstract— **500kW Ocean Energy Isolated Power System demonstration project is the first batch of project, which funded by the National Marine Renewable Energy Special Fund. The 2×100kW tidal current energy generation device is an important part of the demonstration project. The hydrodynamic performance analysis of tidal current turbine is the most critical basic work in the design of turbine, and it is the foundation for subsequent design and analysis of tidal current energy generation device design. Based on the Tidal Bladed software, the calculation model hydrodynamic performance of the turbine of 2×100kW tidal current energy generation device was established in this paper. The efficiency curve and load of turbine have been calculated under steady flow velocity, and the influence of tower shadow and turbulence intensity on the hydrodynamic performance of the turbine have been studied.**

***Keywords*—Tidal current energy turbine, hydrodynamic performance, Tidal Bladed, tower shadow, turbulence intensity.**

I. INTRODUCTION

Tidal current energy, which is one of renewable ocean energy, is clean and rich in resources. Tidal current energy can be one of the most valuable and promising ocean energy forms because of its large energy flow density and strong predictability. In recent years, with the increasing invest of tidal current energy development and utilization technology in the world, tidal current energy development and utilization technology has been progressing towards commercial application.[1,2].

The tidal current energy turbine is the core component of the tidal current energy generation device. The operation environment of tidal current turbine is very complex, and its performance prediction is an important basic work in the design and analysis of the tidal current turbine. In this paper, based on the BEM theory, the 2×100kW tidal current turbine in the "500kW Ocean Energy Isolated Power System demonstration project" was chosen as a example, and the operating efficiency curve and load of the turbine have been calculated in stable flow velocity by Tidal Bladed software. What's more, the influence of hydrodynamic performance of tower shadow and turbulence for the tidal current energy turbine have been calculated.

II. THEORETICAL BASIS

Currently, the calculation methods of hydrodynamic performance of tidal current energy turbine in global are based on blade element momentum(BEM), computational fluid dynamics (CFD), etc. The blade element momentum is relatively simple, and its computation is small, so it is convenient for engineering application [3]. At present, most of the software of tidal current turbine performance calculation is developed based on the blade element momentum.

A. Blade theoretical model

Tidal current energy turbines extract energy from the flow by producing a step change in static pressure across the rotor-swept surface. As the fluid approaches the rotor it slows down gradually, resulting in an increase in static pressure. The reduction in static pressure across the rotor disk results in the fluid behind it experiencing a reduction in pressure compared to free stream conditions. As the fluid proceeds downstream the pressure climbs back to the free stream value resulting in a further slowing down of the flow. There is therefore a reduction in the kinetic energy in the flow, some of which is converted into useful energy by the turbine. When the hydrodynamic analysis is carried out on the turbine, the actuator disk model is adopted, and the following formula is[4]:

$$U_d = (1-a)U_0 \qquad （1）$$

$$U_w = (1-2a)U_\infty \qquad （2）$$

where： U_d - The flow velocity at the rotor disk； U_∞ - Initial flow velocity (upstream flow velocity)； a - The axial flow induction factor (inflow factor)； U_w -velocity in the wake

By applying Bernoulli's equation and assuming the flow to be uniform and incompressible, it can be shown that the power P extracted by the rotor is given by :

$$P = 2\rho AU_0{}^3 a(1-a)^2 \tag{3}$$

The thrust T acting on the rotor disk can similarly be derived to give:

$$T = 2\rho AU_0{}^2 a(1-a) \tag{4}$$

The power coefficient is:

$$C_P = \frac{P}{\frac{1}{2}\rho AU_\infty} = 4a(1-a)^2 \tag{5}$$

where: $\frac{1}{2}\rho AU_\infty$ - All the kinetic energy provided by the tidal current under the condition of no momentum is obtained through the rotating surface of the blade.

When $a = \frac{1}{3}$, the maximal value of the power coefficient C_P occurs and is equal to $\frac{16}{27}$, which is known as the Baez limit.

The thrust coefficient is:

$$C_T = \frac{T}{\frac{1}{2}\rho AU_\infty} = 4a(1-a) \tag{6}$$

When $a = \frac{1}{2}$, the thrust coefficient C_T has a maximal value of 1.

The experiment shows that if $a < 0.4$, the ideal turbine assumption is applicable, if $a > 0.4$, the simple momentum theory is no longer applicable since the velocity step $U_\infty - U_w$ is too large, The unsteady shear flow at the edge of the wake field will lead to turbulence wake.

The actuator disk concept used above allows an estimate of the energy extracted from the flow without considering that the power absorbed by the rotor is the product of torque Q and angular velocity Ω of the rotor.

The torque developed by the rotor must impart an equal and opposite rate of change of angular momentum to the flow and therefore induces a tangential velocity to the flow. The change in tangential velocity is expressed in terms of a tangential flow induction factor b. Upstream of the rotor disk the tangential velocity is zero, at the disk the tangential velocity at radius r on the rotor is Ωrb and far downstream the tangential velocity is $2\Omega rb$. Because it is produced in reaction to the torque, the tangential velocity is opposed to the motion of the blades.

The torque generated by the rotor is equal to the rate of change of angular momentum and can be derived as[5]:

$$Q = \pi R^4 (1-a) bU_\infty \Omega \tag{7}$$

B. BEM

Combined blade element and momentum theory is an extension of the actuator disk theory described above. The rotor blades are divided into a number of blade elements and the theory outlined above used not for the rotor disk as a whole but for a series of annuli swept out by each blade element and where each annulus is assumed to act in the same way as an independent actuator disk[6]. Because of the flow of fluid, the force generated on the blade plane can be decomposed into lift L and drag D. The lift L and drag D on each blade element can be obtained by the following equation:

$$\begin{gathered} L = \frac{1}{2}\rho c C_L U_0^2 \\ D = \frac{1}{2}\rho c C_d U_0^2 \end{gathered} \tag{8}$$

Where: C_L, C_d -coefficient of lift and drag, which have relationship with the shape of the blade foil and attack angle α.

The thrust dT developed by a blade element of length dr located at a radius r is given by:

$$dT = P_N dr = (L\cos\varphi + D\sin\varphi) dr \tag{9}$$

The torque dM developed by a blade element of length dr located at a radius r is given by:

$$dM = rP_T dr = r(L\sin\varphi - D\cos\varphi) dr \tag{10}$$

which: P_T -the force parallel to the rotor disk; P_N -the force perpendicular to the rotor disk.

When the fluid flows around the blade section, it will produce vortex wake, which will cause the fluctuation of blade speed, reduce the torque and cause tip loss[7]. In order to correct this loss, the Prandtl tip loss factor F is used:

$$\begin{gathered} f = \frac{B}{2}\frac{R-r}{r\sin\phi} \\ F = \frac{2}{\pi}\cos^{-1}(e^{-f}) \end{gathered} \tag{11}$$

Where: B -the number of blades; R -blade radius; r -local radius; ϕ -inflow angle.

The thrust of the volume in the plane of the blade is as follows:

$$dT = 4\pi r\rho U_\infty a(1-a) \tag{12}$$

By means of the momentum moment integral equation on the control volume, the torque of the ring element is obtained by:

$$dM = 4\pi r^3 \rho U_\infty a(1-a) bF dr \tag{13}$$

By using the formula (9) and formula (12), the axial induction factor a can be obtained as follows:

$$a = \frac{g_1}{1+g_1} \tag{15}$$

$$g_1 = \frac{Bc}{2\pi r}\frac{(C_L\cos\phi + C_D\sin\phi)}{4F\sin^2\phi}H \qquad (16)$$

The parameter H is defined as follows:

for $a \le 0.3539$, $H = 1.0$

for $a > 0.3539$,

$$H = \frac{4a(1-a)}{(0.6 + 0.61a + 0.79a^2)} \qquad (17)$$

By using the formula (10) and formula (13), the axial induction factor b can be obtained as follows:

$$b = \frac{g_2}{1+g_2} \qquad (18)$$

$$g_2 = \frac{Bc}{2\pi r}\frac{(C_L\sin\phi - C_D\cos\phi)}{4F\sin\phi\cos\phi} \qquad (19)$$

III. 2×100KW TIDAL CURRENT ENERGYTURBINE PARAMETERS

The 2×100kW floating support structure tidal current energy generation device(100kW device) was developed by CNOOC Research Institute and Harbin Engineering University, using a horizontal axis with two blade turbine. The 2×100kW tidal current energy device is shown as Fig. 1.

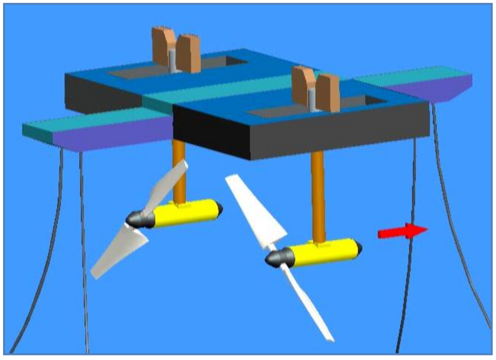


Fig. 1 The sketch of 2×100kW floating support structure horizontal-axis tidal current energy generation device

The basic design parameters of 100kW tidal current energy turbine are shown in Table I.

TABLE II

THE PARAMETERS OF THE TIDAL TURBINE

Parameters	**Value**	**Unit**
Number of blades -N	2	
Diameter of turbine - D	12	m
Rated power	2×100	kW
Rated speed	1.7	m/s
Rated rotating speed	14	rpm

The airfoil profile of 100kW turbine chose the S series of the special profile for the wind turbine, and the design method was Glauert method[8]. The relationships between chord length, twist angle and blade radius are shown in fig. 2 and Fig. 3.

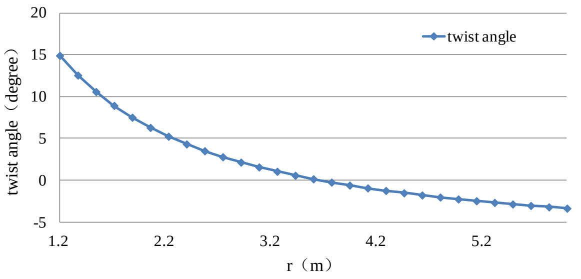


Fig. 2 Twist angle varies with r.

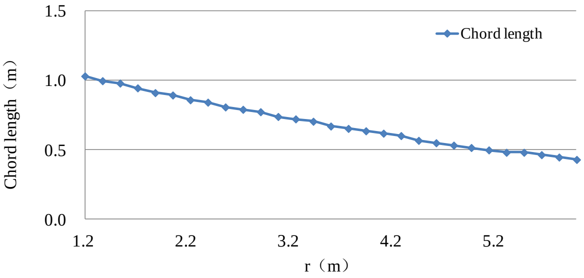


Fig. 3 Chord length versus r.

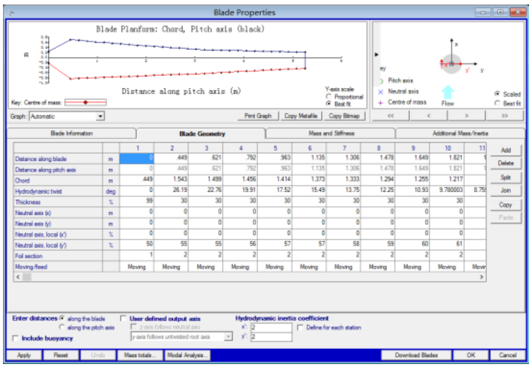
IV. PERFORMANCE CALCULATION AND RESULTS

The software Tidal Bladed based on BEM is developed by the DNV GL company for the calculation of the performance of tidal current turbine. This software is developed from Bladed, which is widely used in the field of wind power[9]. The Tidal Bladed software can calculate and simulate the hydrodynamics and structural mechanics characteristics of the whole tidal current energy generating device.

A. *Calculation model*

The Tidal Bladed software modeling part mainly includes the blade model "Blades", the airfoil definition "Hydrofoil", the turbine "Rotor", the tower "Tower", the transmission system "Power Train", the nacelle "Nacelle", the control system "Control", the wind model "Wind", the sea condition "Sea" and etc, each module has its own shortcut.

The 2×100kW tidal current turbine can design the blade parameters according to the design data, including the blade shape (chord length and twist angle) and etc., as shown in Fig. 4.



		1	2	3	4	5	6	7	8	9	10	11
Distance along blade	m	0	.449	.621	.792	.963	1.135	1.306	1.478	1.649	1.821	1
Distance along pitch axis	m	0	.449	.621	.792	.963	1.135	1.306	1.478	1.649	1.821	1
Chord	m	.449	1.543	1.499	1.456	1.414	1.373	1.333	1.294	1.255	1.217	
Hydrodynamic twist	deg	0	26.19	22.76	19.91	17.52	15.49	13.75	12.25	10.93	9.780003	8.75
Thickness	%	99	30	30	30	30	30	30	30	30	30	
Neutral axis (x)	m	0	0	0	0	0	0	0	0	0	0	
Neutral axis (y)	m	0	0	0	0	0	0	0	0	0	0	
Neutral axis, local (x')	%	0	0	0	0	0	0	0	0	0	0	
Neutral axis, local (y')	%	50	55	55	56	57	57	58	59	60	61	
Foil section		1	2	2	2	2	2	2	2	2	2	
Moving/fixed		Moving	Moving	Moving	Moving	Moving	Moving	Moving	Moving	Moving	Moving	Movi

Enter distances ● along the blade ○ along the pitch axis

☐ Include buoyancy

☐ User defined output axis

☐ z-axis follows neutral axis

y-axis follows untwisted root axis

Hydrodynamic inertia coefficient x': 2 y': 2 ☐ Define for each station

Fig. 4 Blade parameters setting

Then the lift and drag coefficient of the airfoil have been input, and the parameters of blade, hub and the drive system are input. The 100kW tidal current energy turbine calculation model is established as shown in Fig. 5.

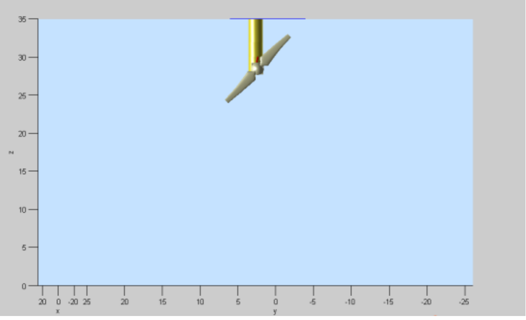


Fig. 5 100kW tidal current energy turbine calculation model

B. *Calculation results*

The calculation of turbine performance is complicated, and the combination of external conditions and operation conditions should be considered. Generally, there are several combinations: normal external condition and normal operating situation: normal external condition and fault situation, extreme external condition and normal operating situation, etc. The external conditions should consider the flow velocity and flow direction change, extreme velocity, environment and so on. The operating situations should consider standby, start up, power production, normal stop, parked, various faults, etc. Considering the above combinations, there are more load cases to be calculated. In this paper, the power production situations are calculated.

Normal operating situation: $V = 1.7 m/s$, rated power operation. Fig. 6 is the calculation result of the efficiency curve of the turbine unit, which shows that the maximum efficiency of the unit is about 44%, and the corresponding tip speed ratio is about 5.

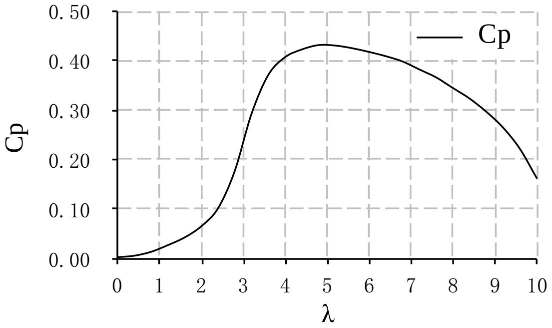


Fig. 6 The efficiency curve

Fig. 2 The efficiency curve the turbine of 2×100kW tidal current energy generation device

Under normal operating situation, the dynamic operating load and power at the blade root of the turbine are shown in Figure 7 and Figure 8. The instantaneous load in the x axis of the blade presents a periodic change, and the curve is smooth, which indicates that the load of the blade is uniformly changed and the relative amplitude of the load change is about 7%. The variation rule of output power is basically the same as that of blade load.

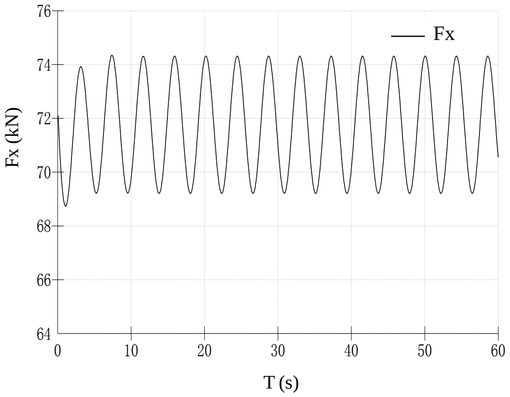


Fig. 7 The change curve of blade force of X Axis with time

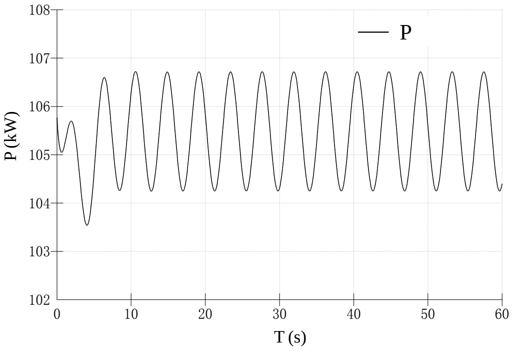


Fig. 8 The instantaneous output power curve of the turbine with time

In the actual operation of the turbine, the operating environment is very complicated, and the tower shadow and the tidal current turbulence are the most influential ones.In the actual operation of the turbine, the operating environment is very complicated, in which the influence of the tower shadow and the tidal current turbulence is great. Fig. 7 and Fig. 8 are compared with the calculation results of the tower shadow and no tower shadow, when there is a tower shadow, the load of the blade and the output power of the turbine also have a periodical change, but the amplitude of the change is obviously increased, and the load change is about 23% relative amplitude. The intense vibration of the load has an important effect on the fatigue of the blades. For instantaneous power, the change amplitude will increase, but the influence of the instantaneous power is less than the load of blades, and the mean of instantaneous power will decrease slightly.

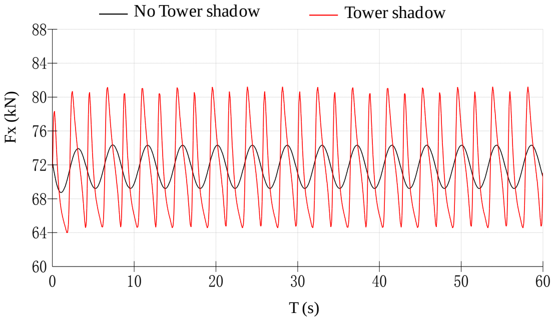


Fig. 9 The effect of tower shadow for the blade force of X Axis

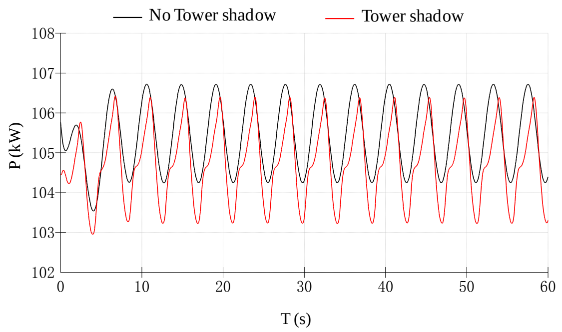


Fig. 10 The effect of tower shadow for output power of the turbine

Fig. 11 and 10 are compared with the calculated results of turbulence (turbulence intensity 3%) and without turbulence. It can be seen from the diagram that, influenced by the turbulence, the blade load and the output power of the turbine have a great fluctuation in each period, especially the capacity of the output power. The violent fluctuation of the output power would bring the challenge to the operation control.

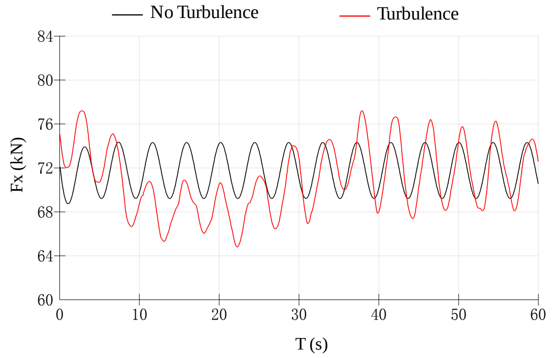


Fig. 11 The effect of turbulence for the blade force of X Axis

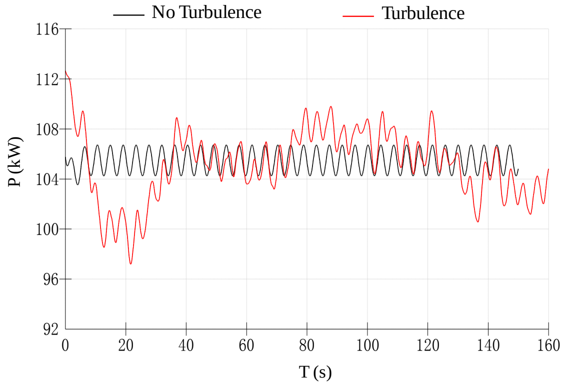


Fig. 12 The effect of turbulence for output power of the turbine

V. CONCLUSION

Based on the classical bladed element momentum theory, the Tidal Bladed software is used to establish the calculation model of the 2×100kW tidal current energy turbine, and the efficiency curve and blade load are calculated under normal operating situation. In the mean time, the effects of tower shadow and tidal current turbulence are calculated and analyzed. The results show that the tower shadow and turbulence have important influence on the blade load and output power of the turbine, and the influence of these factors should be considered in the design. This paper provides a quick and effective method for the performance analysis of tidal current energy turbine in the future.

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REFERENCES

[1] Ma Changlei, Xia Dengwen and Wang Meng, “Review on the Progress of Marine Renewable Energy Technologies in the World,” *Journal of Ocean Technology*, vol. 36(4), pp. 7, 2017.

[2] Renewable UK, “Ocean Energy Race-The UK’s Inside Track,” Rep. 4-7, 2017.

[3] J.F.Manwell, J.G.McGowan and A.L.Rogers, *Wind Energy Explained*: *Theory Design and Application*, Hoboken, America: John Wiley&Sons, Ltd, 2002.

[4] Burton T, Jenkins N and Sharpe D, *Wind Energy Handbook*，2nd ed, Chichester, United Kingdom: John Wiley & Sons, 2011.

[5] *Tidal Bladed Theory Manual*, Garrad Hassan, 2013

[6] He Dexin, *Wind Engineering and Industrial Aerodynamics*, Beijing, China: National Defense Industry Press，2006.

[7] Xiao Jing-song, *Aerodynamics of Wind Turbines*, Beijing, China: China Electric Power Press, 2009.

[8] L. Zhang, ZC. Li, G. Xiao, and L. Zhang, “Research on the key technologies for power generation system with medium and low velocity tidal energy,” *China offshore oil and gas*, vol. 06, pp. 115-118, 2013

[9] X. Liu, W. Jing, W. Lin, “Interactive software platform design based on GH Bladed and Matlab with simulation study of individual pitch controller of wind turbine,” *Proceedings of the CSEE*, vol. 33(22), pp. 83-88, 2013.