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Research paper

Research on analysis method of measurement uncertainty in the power performance assessment of tidal energy converters

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ABSTRACT

The analysis on the measurement uncertainty of output power in the field test of tidal energy converters is an important process to evaluate the power characteristics performance of the tested tidal energy converter. Based on the field test data of the power characteristics performance assessment of a tidal energy converter, the measurement uncertainty calculation results of output power is analyzed. The research results show that: (1) The output power curve with measurement uncertainty information of the tested tidal energy converter that drawn in this paper, can reflect the discreteness and uncertainty of the output power during the field test period; (2) The sensitivity coefficient of tidal current velocity is a component that has a significant impact on the combined uncertainty of output power of tidal energy converters; (3) The change of the output power curve slope of the tested tidal energy converter can reflect the change of the sensitivity coefficient of tidal current velocity. The research results provide a reference for the field test work of power characteristics performance assessment of tidal energy converters in the future.

1. Introduction

The development of human society cannot be separated from the consumption of energy, especially as human society becomes electrified, networked and intelligent, and the demand and consumption of fossil energy are increasing day by day (Zhu et al., 2022). Energy sources such as coal, oil and natural gas are nonrenewable fossil energy with limited reserves, and the use of fossil energy will produce harmful gases such as carbon dioxide and sulfur dioxide, resulting in a series of environmental problems (Liu et al., 2011). In addition, in recent years, affected by regional conflicts and international trade policies, the price of natural gas and other fossil energy has increased a lot (Xia et al., 2022a,b,c). This series of environmental and energy price issues make people pay more and more attention to the development and utilization of green, lowcarbon and pollutionfree clean energy (Yan et al., 2022).

Under the action of tidal forces of celestial bodies such as the moon and the sun, the sea water on the earth's surface shows periodic fluctuations and flows. Especially in the coastal waters, due to the influence of topographic factors such as islands, the tidal current velocity of sea water in the horizontal direction increases significantly, making the sea water have rich kinetic energy. Generally, this kinetic energy of sea water is called tidal current energy (Melikoglu, 2018; Lewis et al., 2019). Tidal current energy is a green, lowcarbon, pollutionfree and renewable clean energy with characteristics of high energy density, strong predictability, energy stability and safety, compared with other types of renewable energy (Li et al., 2019). The development and utilization of tidal current energy resources, on the one hand, is conducive to reducing the consumption and dependence of human society on fossil energy such as coal and oil, and promoting the improvement of the ecological environment; on the other hand, it is conducive to building the industrial chain of tidal energy converters (TECs), creating employment opportunities, and promoting the economic growth of human society (Hou et al., 2019; Sánchez et al., 2022). Because of this, many countries around the world have carried out research and demonstration work, in order to promote the industrial development of TECs.

At the beginning of 2016, Bluewater of the Netherlands cooperated with a group of leading offshore companies to develop BlueTEC Texel power generation prototype. In March 2019, ATIRT unit, a 1.5 MW horizontal axis tidal energy converter developed by Spanish Magallanes Renovables company, was grid connected to national grid for power generation in the European Marine Energy Center (Yeo et al., 2022). In February 2022, the megawatt level horizontal axis tidal energy converter developed by Hangzhou LHD New Energy Research Institute Co., Ltd. was connected to the national grid for power generation in Xiushan Island, Zhoushan City, Zhejiang Province, China. In May 2022,

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the PLATI horizontal axis tidal energy converter developed by SCHOTTEL HYDRO of Germany and Sustainable Marine of the United Kingdom was successfully connected to the grid of the Fundy Ocean Research Center for Energy (FORCE) in Nova Scotia, Canada. As more and more TECs are connected to the grid for power generation, open sea testing is an important means to evaluate the power characteristics performance of TECs (Xia et al., 2022a,b,c; Schmitt et al., 2022).

The field test work of the power characteristics performance of TECs are mostly conducted in the demonstration sea area of the tidal energy converter or at the tidal energy converter open sea test sites. Open sea test sites have become a common step in developing ocean energy in countries across the world and are seen as key innovation hubs for the ocean energy industry. The national tidal energy converter open sea test site of China, is located in the sea area of Zhoushan City, Zhejiang Province, where is rich in tidal current energy resources. However, the topography of Zhoushan sea area changes dramatically, it leads to obvious turbulence effect in this sea area (Yang et al., 2020). Relevant researchers around the world have also studied the turbulence effect in the tidal energy converter test site, which named EMEC (European Marine Energy Center, EMEC) (Osalusi et al., 2009). The tidal current turbulence effect in the sea area where the tidal energy converter is tested will have an impact on the test results of output power of the tested tidal energy converter (Stallard et al., 2015; McCaffrey et al., 2015; Mycek et al., 2014). In addition, technical parameters such as the accuracy level of the output power measuring equipment of the tested tidal energy converter will also have an impact on the output power test results of the tested tidal energy converter (Mingotti et al., 2018).

Measurement uncertainty analysis is an effective method to evaluate the extent to which the output power test results of TECs are affected by the turbulence effects, the measurement equipment accuracy levels and other factors. And in China, relevant scholars have studied the measurement uncertainty calculation method of conversion efficiency in the tank experiments work of tidal power generation prototype (Li et al., 2018). In addition, some researchers around the world have carried out relevant research work on uncertainty evaluation methods in tidal current energy resource evaluation, measurement uncertainty evaluation of tidal energy converter prototype (Polagye and Thomson, 2013; Kutney et al., 2013; Jump et al., 2020). However, there are few studies on the measurement uncertainty analysis method of output power in the power performance assessment of TECs in real sea conditions. Therefore, in order to analysis the influence of the factors such as the turbulence effect of the sea area where the tidal energy converter is tested and the accuracy level of the measuring equipment of the output power, this paper studies the measurement uncertainty analysis method of output power of the tidal energy converter that has been tested in real sea conditions.

2. Methodology

When the measurement uncertainty of output power of the tested tidal energy converter is determined by numbers of influencing factors (such as turbulence, equipment measurement accuracy class, etc.), the combined uncertainty of output power of the tested tidal energy converter in the ith tidal current velocity bine can be calculated as (Xu, 2018),

$$u_{\mathrm{c},i}{}^2 = \sum_{k=1}^{N} \left(\delta(x_k)\right)^2 u^2\left(x_k\right) + 2\sum_{k=1}^{N-1}\sum_{j=k+1}^{N} \delta(x_k)\delta(x_j)\cdot u\left(x_k, x_j\right) \tag{1}$$

$$u\left(x_k, x_j\right) = r\left(x_k, x_j\right) u\left(x_k\right) u\left(x_j\right) \tag{2}$$

where $u_{\mathrm{c,i}}$ is the combined uncertainty of output power of the tested tidal energy converter in the ith tidal current velocity bine, $\delta(x_k)$ is the sensitivity coefficient of the kth influencing factor, $u(x_k, x_j)$ is the covariance between x_k and x_j, $r(x_k, x_j)$ is the correlation coefficient between x_k and x_j, $u(x_k)$ is the measurement uncertainty of x_k. N is the number of factors that have a significant influence on the measurement uncertainty.

In practical application, it is almost impossible to explicitly derive the correlation coefficient between all influencing factors (IEC, 2017). Therefore, Eq. (1) can be derived as,

$$u_{\mathrm{c},i}{}^2 = \frac{\sigma_i{}^2}{n_i} + u_{\mathrm{p},i}{}^2 + \left(\delta(x_{\mathrm{v},i})\right)^2 \cdot u_{\mathrm{v},i}{}^2 \tag{3}$$

where σ_i is the standard deviation of electric power data in the ith bine, n_i is the number of electric power data in the ith bine, $u_{\mathrm{p},i}$ is the measurement uncertainty of category B of the output power in the ith tidal current velocity bine, $\delta(x_{\mathrm{v},i})$ is the sensitivity coefficient of the tidal current velocity in the ith bine, $u_{\mathrm{v},i}$ is the measurement uncertainty of category B of the tidal current velocity in the ith tidal current velocity bine.

It is worth noting that, in the field test and evaluation work of power characteristics performance of TECs, the output power of the tested tidal energy converter is characterized by two dimensional power characteristics curve. The horizontal axis of the power curve is the tidal current velocity value, and the vertical axis is the output power value of the tested tidal energy converter. Therefore, in order to measure the measurement uncertainty of output power of the tested tidal energy converter, it is necessary to calculate the measurement uncertainty of tidal current velocity, which has a propagation effect on the measurement uncertainty of output power of the tested tidal energy converter. And, the sensitivity coefficient of tidal current velocity is used to reflect the influence of the measurement uncertainty of tidal current velocity on the measurement uncertainty of output power of the tested tidal energy converter, that is, to measure the propagation effect of the measurement uncertainty of tidal current velocity.

The measurement uncertainty of annual energy production of the tested TEC can be calculated as (IEC, 2017),

$$u_{\mathrm{AEP}}{}^2 = 8760^2 \cdot \left[\sum_{i=1}^{M} f_i{}^2 \cdot \frac{\sigma_i{}^2}{n_i} + \left(\sum_{i=1}^{M} f_i \cdot \sqrt{\left(u_{\mathrm{p},i}{}^2 + \left(\delta(x_{\mathrm{v},i})\right)^2 \cdot u_{\mathrm{v},i}{}^2\right)}\right)^2\right] \tag{4}$$

where u_{AEP} is the measurement uncertainty of annual energy production of the tested TEC, f_i represents the distribution frequency of tidal current velocity in the ith velocity bine, M is the total number of the tidal current velocity bines.

The expanded uncertainty of the output power and annual energy production can be calculated as (Ferrero and Scotti, 2022),

$$U_{c,i} = \gamma \cdot u_{c,i} \tag{5}$$

$$U_{\mathrm{AEP}} = \gamma \cdot u_{\mathrm{AEP}} \tag{6}$$

where $U_{c,i}$ is the expanded uncertainty of output power of the tested TEC, U_{AEP} is the expanded uncertainty of annual energy production of the tested TEC, γ is a coverage factor, whose value is usually 2, representing that the confidence level of expanded uncertainty is 95.5% (Ferrero and Scotti, 2022).

3. Case study

After the deployment of TEC, the field test work was carried out to measure the output power of the tested TEC and the input energy of tidal current velocity, according to the field test method for power characteristics performance assessment of TECs, IEC

Fig. 1. The deployment of tidal energy converter.

Table 1
The accuracy class of the measurement devices.

Measurement elements	Velocity	Voltage	Current	Power
Accuracy class	0.25%	0.1%	0.1%	0.1%

62600200 (IEC, 2013). The field test time is from June to July 2019, and it is introduced previously (Wang et al., 2022a,b; Xia et al., 2022a,b,c) (see Fig. 1).

In addition, the measurement uncertainty of category B of the output power and the tidal current velocity in the ith tidal current velocity bine, represented by $u_{\mathrm{p},i}$ and $u_{\mathrm{v},i}$, are mainly related to the accuracy class and the range of the output power and tidal current velocity measurement devices, and the rated power of the tested TEC. The accuracy class of the measurement devices that used in the field test of TEC is shown in Table 1.

4. Results

During the field test period, due to the periodic and reciprocating changes of the flood tide and ebb tide, the tested TEC does not always generate electric power. In addition, due to the overhaul and maintenance of the tested TEC during the field test period, the TEC is also not always generate electric power. Therefore, the data at the time when the TEC does not generate electric power shall be deleted first. Then, according to the measurement uncertainty calculation method of output power for the tested TEC that studied in this paper, taking the rated power of the tested TEC and the measurement devices accuracy class during the field test period into consideration, the measurement uncertainty of category B of the output power and the tidal current velocity in the ith tidal current velocity bine, represented by $u_{\mathrm{p},i}$ and $u_{\mathrm{v},i}$, can be derived as,

$$u_{\mathrm{p},i}{}^2 = (0.09\% \cdot P_i)^2 + (0.06\% \cdot P_i)^2 + (0.26)^2 + (0.45)^2 \tag{7}$$

$$u_{\mathrm{v},i}{}^2 = (3\% \cdot v_i)^2 + (0.14\% \cdot v_i)^2 + (0.5\%)^2 \tag{8}$$

The calculation results of the measurement uncertainty of the output power are shown in Table 2. In Table 2, s_i represents the calculation results of measurement uncertainty of category A of the tested TEC under the ith tidal current velocity bine, f_i represents the distribution frequency of tidal current velocity in the ith velocity bine, u_i is the measurement uncertainty of category B of the tested TEC under the ith tidal current velocity bine. In addition, because there is only one data point in the last tidal current velocity bine, Bessel's Correction Equation is not applicable. Therefore, the measurement uncertainty of category A of output power for the tested TEC in the last tidal current velocity bine has not been calculated.

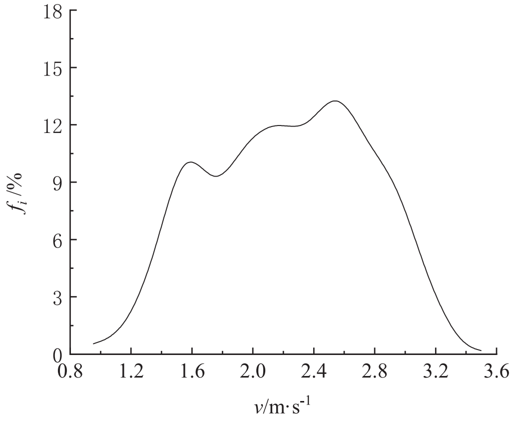

Fig. 2. The distribution frequency curve of tidal current velocity.

Assuming that the availability of the tested TEC is 100%, the annual energy production of the tested TEC can be calculated as (Xia et al., 2022a,b,c),

$$AEP = 8760 \cdot \sum_{i=1}^{N} f_i \cdot p_i \tag{9}$$

According to Eqs. (6) and (9), the estimated annual energy production of the tested TEC is about 513 840.9 kWh, and the expanded uncertainty of the estimated annual energy production is 94 483.4 kWh, when the coverage factor is 2.

5. Discussion

5.1. Distribution frequency curve of tidal current velocity

In order to characterize the distribution of tidal current velocity during field test period, the distribution frequency curve of tidal current velocity during field test period is drawn according to the test data in Table 2. The results are shown in Fig. 2.

It can be seen from Fig. 2 that during the field test period, the distribution frequency of tidal current velocity is relatively high in the range of 1.5∼3.0 m/s, and relatively low in other velocity bines, especially in the first two velocity bines and the last two velocity bines. The data distribution frequency of tidal current velocity within the range of 2.5∼2.6 m/s is the highest, and the value is about 14.2%.

5.2. Output power curve with measurement uncertainty information

As it is mentioned previously, the output power of the tested TEC is characterized by two dimensional power characteristics curve. Therefore, in order to measure the uncertainty of the output power of the tested TEC, according to the combined uncertainty calculation results in Table 2, the output power curve with measurement uncertainty information has been drawn, as it is shown in Fig. 3. And the changes curve of the combined uncertainty has also been drawn, as it is shown in Fig. 4.

It can be seen from Fig. 3, compared with a single output power curve or output power scatter diagram that has been drawn before (Xia et al., 2022a,b,c; Wang et al., 2022a,b; Lewis et al., 2019; DíazDorado et al., 2021), the output power curve with measurement uncertainty information can better measure the dispersion of output power of the tested TEC in each tidal current velocity bine. In addition, it can be seen from Fig. 4 that the maximum value of the combined uncertainty of the tested TEC is 9.74 kW, about 3.25% of the rated power.

Table 2
The calculation results of measurement uncertainty.

NO.	Velocity bine (m/s)	v_i (m/s)	p_i (kW)	$u_{c,i}$ (kW)	s_i (kW)	u_i (kW)	$u_{v,i}$ (m/s)	$u_{p,i}$ (kW)	$\delta(x_{v,i})$ (kW s/m)	f_i (%)
1	0.9∼1.0	0.95	2.38	1.23	1.09	0.57	0.03	0.52	7.86	0.54
2	1.1∼1.2	1.15	5.03	0.91	0.58	0.70	0.03	0.52	13.42	1.08
3	1.3∼1.4	1.35	7.51	1.01	0.48	0.89	0.04	0.52	17.69	4.86
4	1.5∼1.6	1.55	12.10	1.68	0.49	1.61	0.05	0.52	32.49	11.53
5	1.7∼1.8	1.75	19.82	2.62	0.69	2.52	0.05	0.52	46.74	8.29
6	1.9∼2.0	1.95	30.80	3.55	1.11	3.37	0.06	0.52	56.61	11.17
7	2.1∼2.2	2.15	43.18	4.65	1.01	4.54	0.06	0.52	69.57	12.25
8	2.3∼2.4	2.35	58.62	6.20	1.30	6.06	0.07	0.52	85.33	11.53
9	2.5∼2.6	2.55	77.52	8.57	1.48	8.44	0.08	0.53	109.82	14.23
10	2.7∼2.8	2.75	102.07	9.74	1.97	9.54	0.08	0.53	115.09	10.99
11	2.9∼3.0	2.95	123.56	7.28	1.93	7.02	0.09	0.54	78.83	9.01
12	3.1∼3.2	3.15	132.91	5.86	2.46	5.32	0.09	0.54	55.86	3.78
13	3.3∼3.4	3.35	145.90	6.85	1.62	6.65	0.10	0.54	65.83	0.54
14	3.5∼3.6	3.50	156.79	7.66	/	7.66	0.11	0.55	72.57	0.18

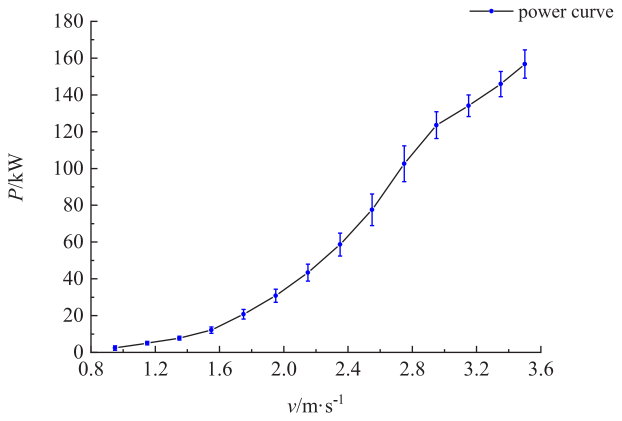

Fig. 3. The output power curve of the tested tidal energy converter with the measurement uncertainty information.

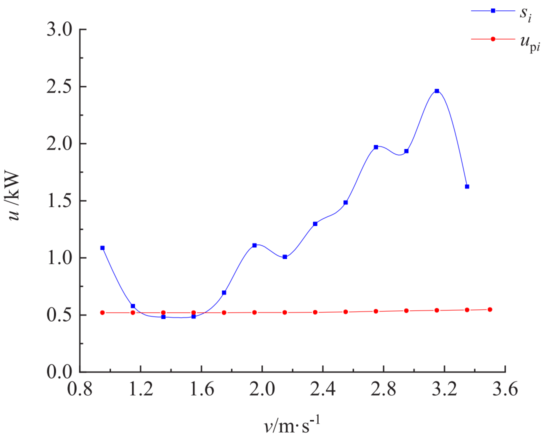

Fig. 5. The changes curves of category A uncertainty and category B uncertainty of output power.

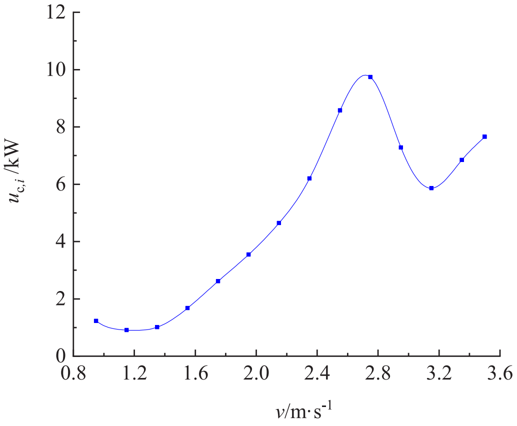

Fig. 4. The changes curve of the combined uncertainty.

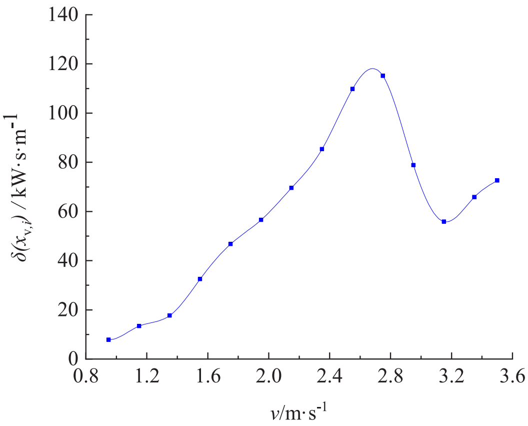

Fig. 6. The changes curve of the sensitivity coefficient of the tidal current velocity.

5.3. Analysis the components of combined uncertainty

It can be seen from Eq. (3) that the combined uncertainty of output power of the tested TEC is mainly affected by four components, s_i, $u_{p,i}$, $\delta(x_{v,i})$, and $u_{v,i}$. Therefore, using the calculation results in Table 2, the changes of s_i, $u_{p,i}$, $\delta(x_{v,i})$, and $u_{v,i}$ with tidal current velocity is plotted. The results are shown in Figs. 5–7.

Through the analysis of Figs. 5–7, it can be found that the changes curve of the sensitivity coefficient of the tidal current velocity that represented in Fig. 6 is consistent with the changes curve of the combined uncertainty of output power of the tested TEC that represented in Fig. 4. And the sensitivity coefficient has a large magnitude, which can be considered as a component that has a significant impact on the combined uncertainty of output power of the tested TEC. In addition, as it is studied previously, the sensitivity coefficient is used to measure the propagation effect of the measurement uncertainty of tidal current velocity, and the physical meaning of the sensitivity coefficient is the output power slope. Therefore, the changes of the combined uncertainty curve of output power of the tested TEC is also reflected in the changes of the curve slope in Fig. 3.

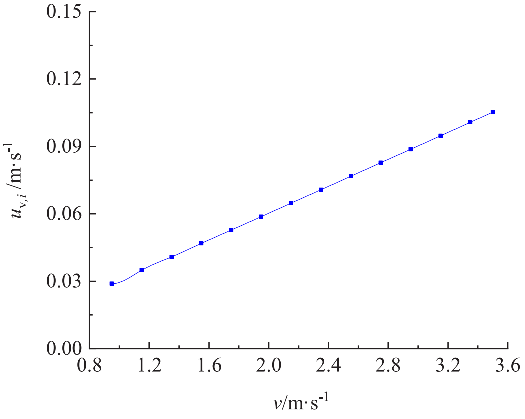

Fig. 7. The changes curve of category B combined uncertainty of tidal current velocity.

5.4. Analysis the change of output power curve slope

It can be seen from Fig. 3 that the slope of output power curve of the tested TEC decreases when the tidal current velocity exceeds 3 m/s. Its physical meaning is that with the increase of tidal current velocity, the increase magnitude of output power of the tested TEC decreases. The relationship between the output power of TECs and the tidal current velocity that input into the energy capture cross section of the tested TEC is as follows (Wang et al., 2022a,b),

$$P_j = \frac{1}{2}\rho A v_j^{\,3} \cdot \eta_j \tag{10}$$

where p_j is the output power of TECs, ρ is the density of seawater, v_j is the tidal current velocity, η_j is the overall conversion efficiency of the tested TEC.

It can be seen from Eq. (6) that the output power of the tested TEC is not only related to the tidal current velocity, but also related to the area of the energy capture cross section and the overall conversion efficiency of the tested tidal energy converter. The influence of tidal current velocity, area, conversion efficiency and other factors on the output power of TECs can be represented by the parameter named "tip speed ratio" (DíazDorado et al., 2021; Martinez et al., 2021; Jo et al., 2014; Cai et al., 2022). In addition, it can be seen from the calculation results in Table 2 that the total number of the tidal current velocity data in the last three tidal current velocity bines that exceed 3 m/s, totally account for about 4.5% of the total number of the test data, it means that the number of the field test data exceeding 3 m/s is relatively few. Therefore, the changes of the output power curve slope of the tested TEC in Fig. 3 may be caused by the "tip speed ratio" of the tested TEC after the tidal current velocity exceeds 3 m/s, or the changes of the number of the field test data.

6. Conclusions

In order to analyze the measurement uncertainty results of output power of the tested TEC, this paper studies the calculation method of the measurement uncertainty of output power of TECs, and applies the field test data of the power characteristics assessment of the tested TEC to calculate the combined uncertainty, category A uncertainty, category B uncertainty, and the sensitivity coefficient of tidal current velocity. The following conclusions are described by analyzing and discussing the output power curve, the measurement uncertainty components, and the changes of output power curve slope:

(1) The output power curve of the tested TEC drawn in this paper, which contains the measurement uncertainty information of output power, can not only reflect the discreteness of output power data of the tested TEC during the field test period, but also can more clearly indicate the measurement uncertainty of output power of the tested TEC in each tidal current velocity bine.

(2) The sensitivity coefficient of tidal current velocity is consistent with the change trend of the combined uncertainty curve of output power of the tested TEC, and the magnitude of the sensitivity coefficient is large. It is considered as a component that has a significant impact on the combined uncertainty of output power of the tested TEC.

(3) The main factor that affecting the sensitivity coefficient of tidal current velocity is the change of the power curve slope of the tested TEC, while the tip speed ratio and the amount of the test data that obtained in each tidal current velocity bine will affect the slope of the output power curve. Therefore, in the future field test work for power performance assessment of TECs, on the one hand, the change of tip speed ratio of TECs should be studied, in order to analyze the change mechanism of output power of TECs. On the other hand, taking the power supply of the measurement devices and the test period into consideration, and the sampling frequency of measurement devices shall be appropriately increased, so as to improve the ability to capture the data of tidal current velocity and output power of the tested TEC under the high tidal current velocity condition.

In summary, the measurement uncertainty analysis method of output power that proposed in this paper, can well measure the dispersion of output power data of the tested TEC in each tidal current velocity bine, and can improve the credibility of the power characteristics field test results of TECs. With the continuous development of demonstration work of TECs, more and more TECs will carry out power characteristics field test work in real sea conditions. The measurement uncertainty analysis method of output power of TECs that proposed in this paper will have a broad application prospect. The research results of this paper provide a reference for analyzing and evaluating the output power of TECs scientifically and accurately, and will certainly promote the commercial application and industrial development of TECs.

CRediT authorship contribution statement

Hainan Xia: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Xiangnan Wang:** Conceptualization. **Qiang Li:** Methodology. **Ning Jia:** Writing – review & editing. **Yuanfei Zhang:** Investigation.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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