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Power Performance Assessment for the Energy Storage Type of Wave Energy Converter

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Abstract. This paper discusses the energy matching problem between wave energy input and generator power output, in the power performance assessment for the energy storage type of wave energy converter. Under the small wave condition, the power performance of the energy storage type of wave energy converter is researched. The site test data processing method is analyzed, and the calculation method of the average conversion efficiency and the annual energy production are optimized. The results show that the optimized power performance analysis method can more accurately assess the power performance matrix of the wave energy converter, and improve the calculation accuracy of the average conversion efficiency and the annual energy production of the wave energy converter. The research results provide an effective method for more scientific and accurate evaluation of power performance indexes of the energy storage type of wave energy converters.

Keywords. Wave energy converter, site test data processing method, optimized power performance analysis method

1. Introduction

The phenomenon of wave is an important form of movement in the ocean, and this movement makes waves have huge energy [1]. From a global perspective, the storage capacity of wave energy resources is abundant, and the development and utilization of wave energy resources have very broad prospects [2]. Wave energy is a green, clean and environmentally friendly energy source, and the development and utilization of wave energy resources are of great significance for the aspects of reducing fossil energy consumption, optimizing China’s energy structure, and promoting the green sustainable development of the economy and society of China [3].

In recent years, various countries in the world have been increasing investments in research and development of wave energy converters [4]. The development and utilization technologies of wave energy resources have been advancing continuously, and a large number of wave energy converters have been used to conduct significant operation work in the real sea condition [5]. Crestwing company of Denmark,

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developed a TordenskioId wave energy converter, with an installed capacity of 20 kW, and an operating water depth of about 20 m. The TordenskioId completed more than five months of trial work in the real sea condition in Kattegat, in the Autumn of 2018. In the Autumn of 2019, AW-Energy company of Portugal completed the assembly and distribution of a WaveRoller wave energy converter, with an installed capacity of 350 kW. The WaveRoller started to generate power in the middle of November, and connected to the national grid through an on-shore substation [6]. In April 2017, the upgraded and improved Eagle-type converter “WanShan” was conducted a significant application operation in the sea area of Dawanshan Island in Zhuhai City, with the wave energy installed capacity of 240 kW. In November 2019, “PengHu” wave energy converter with an installed capacity of 120 kW, developed by YouLian Dockyards (Shekou) Co., Ltd., Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences was used to conduct a significant application in the real sea condition in the Guishan Island in Zhuhai city, Guangdong province [7]. During a significant application process of the wave energy converter, the power performance site testing work was an important basis for verifying the power generation performance of the wave energy converter [8].

In the field of power performance assessment of a wave energy converter, Chinese and overseas researchers of relevant research institutions, have conducted a large amount of research work [9]. However, the significant wave height, and the wave power of the off-shore wave energy resources of China are smaller than those of European countries on the coast of Atlantic. Under this condition, the relevant testing methods of overseas cannot be completely applied to the site testing work in China. Therefore, in this article, research was conducted on the power performance assessment for the energy storage type of wave energy converter, under the small wave condition. The site test data is used for verification, to provide a reference for more reasonably evaluating power performance indexes of wave energy converter.

2. Energy Storage Type Wave Energy Converter

According to the power generation principle of the energy storage type of wave energy converter, the energy storage type of wave energy converter can be divided into two parts: a wave energy capture system and a power conversion system [10]. The wave energy capture system converts wave energy into mechanical energy by using physical structures, such as a float or a pendulum plate. The power conversion system converts the captured mechanical energy into hydraulic energy, and stores in the energy storage system, and when the pressure of the energy storage system reaches a set value, the high-pressure hydraulic oil drives a hydraulic motor to generate power, and finally, the hydraulic energy is converted into electrical energy.

3. Power Performance Analysis

3.1. Data Recording Period

When power performance analysis is performed on a wave energy converter, calculating the wave energy that input into the wave energy converter and the output energy that wave energy converter is required. The calculation of the wave energy needs to measure the significant wave height and wave period of a tested sea area, and the significant wave height and wave period are statistical values within a certain time range. Taking a wave rider buoy as an example, the wave data recording period of this device is 1800 s.

3.2. Test Data Analysis

During the site testing period, there are cases where the wave energy is small and varies. In this case, although the wave energy of the tested sea area is continuously converted and stored in the energy storage system, the energy storage system of the energy storage type of wave energy converter will drive the hydraulic motor to generate power only when a set pressure value is reached. Therefore, site test data cannot be fully applied to power performance analysis, and data to be removed will be discussed in the following two situations.

3.2.1. Power Generation in Data Recording Period

The power generation process of the wave energy converter is in a data recording period; however, in a certain data recording period, the wave energy converter does not generate power, and power is generated in an adjacent next data recording period, as shown in table 1.

It can be determined from the analysis of table 1 that the significant wave height variation range of the tested sea area during this period of time is 0.24 m to 0.26 m, the wave period variation range is 2.7 s to 2.9 s, and the wave energy converter only generates power in three test data recording periods. In particular, it can be determined from the comparison between the sixth and seventh sets of data that in the case of the same significant wave height of the tested sea area, the wave period is reduced, but the wave energy converter generates power, and this shows that the seventh set of power generation data is energy storage in the time range of 3:00 to 4:00. Such type of power generation data leads to a high calculation result of the average conversion efficiency of the energy storage type of wave energy converter, and needs to be removed.

Table 1. Power generation data in data recording period.

Serial number	Time	Significant wave height (m)	Period (s)	Generated power (W)
1	11/1701:00	0.26	2.9	0.0
2	11/1701:30	0.25	2.9	370.8
3	11/1702:00	0.24	2.7	0.0
4	11/1702:30	0.25	2.9	384.2
5	11/1703:00	0.25	2.8	0.0
6	11/1703:30	0.26	2.9	0.0
7	11/1704:00	0.26	2.8	368.3

3.2.2. Power Generation in Data Recording Period Demarcation Point

The power generation process of the wave energy converter crosses the demarcation point of the data recording period, as shown in figure 1.

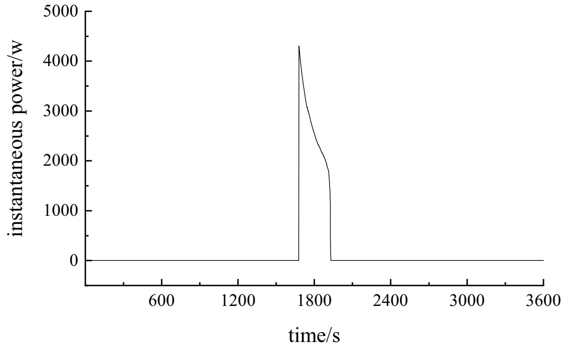

Figure 1. Instantaneous output power diagram of wave energy converter.

It can be determined from the analysis of figure 1 that in the time range of 0 to 3600 s, the wave energy converter only generates power once which lasts for 250 s, and the power generation process crosses the moment 1800 s; however, the test data recording period is 0 to 1800 s. This results in the wave resource statistical period being 1800 s in the data recording period of 0 to 1800 s, and part of the output instantaneous power values being counted into the next data recording period, i.e., the wave input energy does not correspond to the output energy of the wave energy converter. When the power performance of the wave energy converter is analyzed, such type of data needs to be removed.

4. Power Performance Index Calculation

4.1. Conversion Efficiency

The power performance site testing procedure for wave energy converters issued by the International Electrotechnical Commission does not explicitly provide a method for calculating the conversion efficiency of a wave energy converter. However, previous research has proposed using a ratio of an actual capture length of a wave energy converter to a designed capture length as a conversion efficiency calculation method [11]:

$$L_k = \frac{P_k}{J_k} \tag{1}$$

$$\eta_k = \frac{L_k}{\mathrm{C}} \tag{2}$$

where k is the k-th data recording period; L_k is the actual capture length of the wave energy converter, and the unit is m; P_k is the average output power of the wave energy converter, and the unit is kW; J_k is the wave energy flux of the tested sea area, and the unit is kW/m; η_k is the average conversion efficiency of the wave energy converter; and C is the capture length designed for the wave energy converter, and the unit is m.

After the average conversion efficiency η_k of the wave energy converter in each data recording period is calculated, the average conversion efficiency of the wave energy converter during the whole testing period is calculated according to equation (3):

$$\eta_a = \sum_{i=1}^{N_b} (\eta_i \bullet f_i) \tag{3}$$

where η_a is the average conversion efficiency of the wave energy converter during the whole testing period; η_i is the average conversion efficiency of the wave energy converter in the i-th interval after interval processing [6]; f_i is the distribution frequency of conversion efficiencies in the i-th interval; and N_b is the total number of divided intervals after interval processing.

According to the physical meaning of η_i and f_i in equation (3), equation (4) can be derived from equation (3) as:

$$\eta_a = \sum_{i=1}^{N_b} \left[\left(\frac{1}{n_i} \bullet \sum_{k=1}^{n_i} \eta_k \right) \bullet \frac{n_i}{N} \right] \tag{4}$$

where n_i is the number of conversion efficiencies of the wave energy converter in the i-th interval; and N is the total amount of conversion efficiency data of the wave energy converter during site testing.

Equation (5) can be further derived from equation (4) as:

$$\eta_a = \frac{1}{N} \sum_{i=1}^{N_b} \sum_{k=1}^{n_i} \eta_k \tag{5}$$

From equation (5), it can be determined that the average conversion efficiency of the wave energy converter during site testing is an average value of the average conversion efficiency data of the wave energy converter in each data recording period.

4.2. Annual Energy Production

In April, 2017, the International Electrotechnical Commission modified the method for estimating the annual energy production of a wave energy converter,

$$P_y = T \bullet \sum_{i=1}^{N_b} L_i \bullet J_i \bullet f_i \tag{6}$$

where T is the annual operating time of the wave energy converter, and the unit is h; P_y is the annual energy production of the wave energy converter, and the unit is kWh; L_i is the average capture length of the wave energy converter in the i-th interval after interval processing, and the unit is m; J_i is the wave energy flux in the i-th interval after interval processing, and the unit is kW/m; and f_i is the distribution frequency of conversion efficiencies in the i-th interval.

Equation (7) can be further derived from equation (6) as:

$$P_y = T \bullet \sum_{i=1}^{N_b} P_i \bullet f_i \tag{7}$$

where P_i is the average electrical power of the wave energy converter in the i-th interval after interval processing, and the unit is kW.

According to the physical meaning of P_i and f_i in equation (7), equation (8) can be derived from equation (7) as:

$$P_y = T \bullet \sum_{i=1}^{N_b} \left[\left(\frac{1}{b_i} \bullet \sum_{k=1}^{b_i} p_k \right) \bullet \frac{b_i}{N} \right] \tag{8}$$

where b_i is the number of output powers of the wave energy converter in the i-th interval; and N is the total amount of output power data of the wave energy converter during site testing.

Equation (9) can be further derived from equation (8) as:

$$P_y = \frac{T}{N} \bullet \sum_{i=1}^{N_b} \sum_{k=1}^{b_i} p_k \tag{9}$$

From equation (9), it can be determined that the estimated value of the annual energy production of the wave energy converter is an average value of the output power data of the wave energy converter in each data recording period.

5. Trial Verification

5.1. Power Generator

The verification object of the optimization method of this article was located in the sea area of Zhuhai city, Guangdong province, as shown in figure 2. The rated output power of the wave energy converter unit was 60 kW, and the rated voltage thereof was 380 V. The testing lasted for 36 days from 13 November 2019 to 18 December 2019.

Figure 2. Wave energy converter.

5.2. Wave Measurement

Wave resource parameters, such as the wave height and wave period, of a tested sea area were measured by using a DWR-Mk III wave measurement buoy, and a data recording period of the wave resource parameters was 30 min. The technique parameters of the DWR-Mk III wave measurement buoy are shown in table 2.

Table 2. DWR-Mk III parameters.

Measurement factors	Range	Accuracy
Wave height	0 to 20 m	0.5% rdg
Period	1.6 s to 30 s	0.5% rdg

5.3. Electrical Power Measurement

The measurement of the output electrical power of a wave energy converter was performed by means of a power analyzer, and was in time synchronization with the wave measurement buoy, and electrical power data was recorded every second. The technical parameters of the power analyzer are shown in table 3.

Table 3. Power analyzer parameters.

Measurement factors	Range	Accuracy
Voltage	0 to 1000 V	0.5% rdg
Current	0 to 500 A	0.5% rdg

6. Results Analysis

6.1. Power Matrix

In the present article, the power performance analysis optimization method for the wave energy converter was applied to process the site test data, and the power matrix diagram of an energy storage type of wave energy converter during the site testing period was drawn, as shown in figure 3.

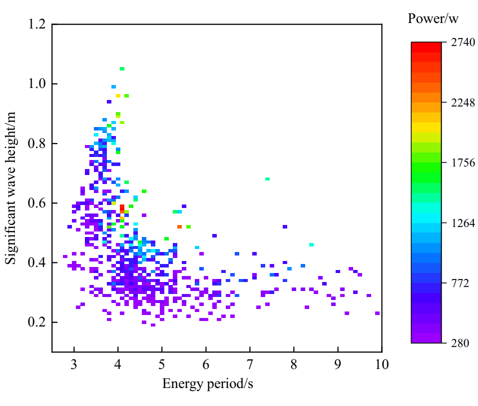

Figure 3. Output power diagram of wave energy converter.

By analyzing figure 2, it can be determined that during the site testing period, the wave amplitude of the tested sea area was low and the energy was small. It can be found by statistical analysis of the test data that about 88.0% of the significant wave height data was less than 0.6 m and about 89.5% of the wave period data was below 6 s.

6.2. Conversion Efficiency

6.2.1. Conversion Efficiency Scatter Diagram

The method proposed in the present article was applied to process the site test data, and the conversion efficiency scatter diagram of the wave energy converter during the site testing period was drawn, as shown in figure 4.

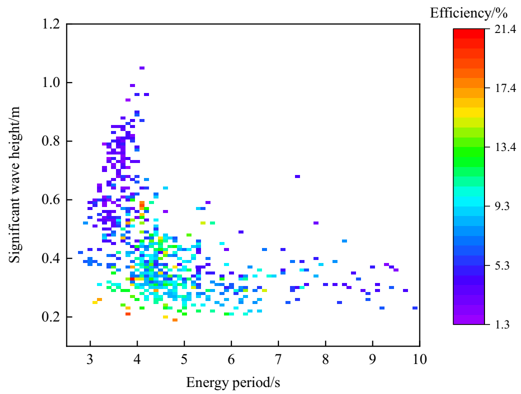

Figure 4. Conversion efficiency scatter diagram of wave energy converter.

By analyzing figure 3, it can be determined that during the site testing period, the conversion efficiency of the wave energy converter under test was mostly above 10% when the significant wave height was 0.2 m to 0.5 m and the wave period was 4 s to 5 s.

6.2.2. Average Conversion Efficiency

Equation (5) and the optimized power performance analysis method were applied to calculate the average conversion efficiency of the wave energy converter from energy capture point to power output point during the site testing period. The calculation result was compared with the non-optimized calculation result, as shown in table 4.

Table 4. Average conversion efficiency comparison.

	Before optimization	**After optimization**
Efficiency (%)	7.8	7.9

From table 4, it can be determined that the average conversion efficiency after optimization was increased by 1.3% compared with the average conversion efficiency before optimization.

6.3. Annual Energy Production

Equation (9) and the optimized power performance analysis method were applied to estimate the annual energy production of the wave energy converter, according to the average electrical power data output by the wave energy converter during the site testing period. The calculation result was compared with an annual energy production estimation value of the unanalyzed energy storage type of wave energy converter under the small wave condition, as shown in table 5.

Table 5. Annual energy production estimation value comparison.

	Before optimization	**After optimization**
Annual energy production (Wh)	5467500	5608400

From table 5, it can be determined that the estimated annual energy production of the wave energy converter after optimization was increased by 2.6% compared with that before optimization.

7. Conclusion

The aims of this article are to analyze the electrical power output performance of the energy storage type of wave energy converter in a small wave condition, the power performance assessment method for the energy storage type of wave energy converter has been researched, the calculation equations of power performance indexes of the wave energy converter have been improved, and the power performance analysis method for the energy storage type of wave energy converter has been optimized. The results show that the power performance assessment optimization method for the wave energy converter proposed in the present article can improve the calculation accuracy of power performance indexes, and provide a reference for more scientific and accurate way to assess the power performance indexes of the energy storage type of wave energy converter.

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References

[1] Feng S Z, Li F Q and Li S J 1999 Wave phenomena in the ocean *An Introduction to Marine Science* (Higher Education Press) Chapter 6 pp 181-182.

[2] Isaacs J D and Schmitt W R 1980 Ocean energy: Forms and prospects *American Association for the Advancement of Science* **207** (4428) 265-273.

[3] Zhang Y Q, Sheng S W and You Y G 2019 Development status and application direction of wave energy generation technology *Advances in New and Renewable Energy* **7** (4) 374-378.

[4] Wang X N, Jia N and Xia H N 2018 Testing and evaluation of China's marine energy generating devices *Ocean Development and Management* **35** (6) 87-90.

[5] Wang X N, Xia H N and Zhang Y F 2020 Site testing and analyzing of wave energy converter *Acta*

Energiae Solaris Sinica **41** (8) 13-20.

[6] Ana B M 2019 *Norway An Overview of Ocean Energy Activities in 2019* (The Executive Committee of Ocean Energy System) p 14.

[7] Peng W, Ma C L and Wang H F 2019 The progress of wave energy *Annual Report of China Ocean Energy Industry 2019* (China Ocean Press) p 15.

[8] Wang X N, Yu Y H and Xia H N 2019 Research on power characteristic field test analysis method of wave energy generation device *Chinese Journal of Scientific Instrument* **40** (1) 70-76.

[9] Gao H T, Guan S F and Zhou D L 2013 Experimental test on a kind of floating type wave energy converter *Acta Energiae Solaris Sinica* **33** (1) 177-180.

[10] Ye Y, Wang K L and Zhang Y Q 2020 Numerical simulation research on energy storage system of wave energy converter *Acta Energiae Solaris Sinica* **41** (8) 30-35.

[11] Sheng S W, Wang K L and Lin H J 2019 Open Sea tests of 100 kW wave energy converter sharp eagle Wanshan *Acta Energiae Solaris Sinica* **40** (3) 709-714.