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Technical Research on Testing and Evaluation of Wave Energy Generation Devices

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Abstract: *As an important component of renewable energy, wave energy has seen rapid growth in installed capacity of wave energy generation devices. Establishing a comprehensive testing and performance evaluation program for wave energy generation devices is crucial for their development. This paper focuses on the power characteristics and power quality characteristics of wave energy generation systems, proposing testing principles, measurement elements, testing methods, and important testing indicators for the power characteristics and power quality. By improving the method of bins, the power characteristic matrix of wave energy generation devices is obtained, and an evaluation system for power quality characteristics is established. The impact of power quality testing on power supply reliability and electrical quality is analysed in detail, providing reference for the performance evaluation system and data analysis methods of wave energy generation devices.*

Keywords: *Wave energy generation, Power performance testing, Power characteristic matrix, Power quality characteristic testing*

1. Introduction

Wave energy conversion devices can be broadly classified into three types based on the principles of energy conversion. The first one is Airflow Generation,The up and down motion of ocean waves causes the movement of air, which in turn drives a turbine to generate electricity. This type of device utilizes the vertical motion of waves to convert wave energy into mechanical energy and then into electrical energy [1]. other one is Mechanical Motion Conversion. This type of device converts the linear or rotational motion of ocean waves into mechanical energy, which is then converted into electrical energy. The device directly harnesses the mechanical motion of the waves to generate electricity. And Potential Energy Conversion, This type of device accumulates water in a high-level reservoir using wave energy. The accumulated water is then released to generate a high-pressure water flow, which impacts a water turbine and converts the potential energy into electrical energy. Researchers and scholars from around the world have conducted corresponding research on these three types of wave energy conversion devices.

Currently, the main methods for constructing on-site testing and evaluation systems for wave energy conversion devices, both domestically and internationally, including: The European Marine Energy Centre Ltd (EMEC) released the Tank Testing of Wave Energy Conversion Systems in 2009. This system introduces methods for assessing wave and tidal energy resources, design principles for testing systems, and operational and testing methods for subsystems. And The International Electrotechnical Commission (IEC) published the IEC TS 62600-100 standard in 2012, titled Electricity producing wave energy converters – Power performance assessment. This standard investigates the testing principles and methods used in power performance assessment of wave energy converters. It sets strict requirements and provides corresponding explanations for site assessment, testing procedures, data collection, and data processing related to the power performance of wave energy converters.

With the development of power generation technologies, new types of ocean energy conversion devices are gradually being proposed, and the establishment of on-site testing and comprehensive performance evaluation systems for these devices is an inevitable requirement [2]. The research and development level of wave energy conversion devices in China is still in the experimental stage, and there is still a long way to go before commercial operation. The performance testing system for wave energy conversion devices is also in its early stages. Therefore, it is of great significance to analyze the application significance of power characteristics and power quality characteristics testing, propose specific indicators to be analyzed in the characteristic testing system, and analyze the testing methods and data processing methods for each indicator.

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2. Wave Energy Performance Testing System

This paper, based on the analysis of the International Electrotechnical Commission's standards for testing and evaluation of wave energy conversion devices and referring to the characteristics testing standards for wind turbines, divides the overall testing system into two subsystems: power performance testing and power quality testing. It explains the testing methods for power performance and power quality, and derives the data analysis and indicator calculation processes.

The power performance testing subsystem focuses on evaluating the power output and efficiency of the wave energy conversion device. It includes measuring the wave energy resource, assessing the device's power generation capability, and analyzing its power conversion efficiency. Various parameters and indicators are calculated, such as the captured power, average power output, and capacity factor.

The power quality testing subsystem assesses the quality of the electrical energy generated by the device. It involves measuring parameters such as voltage, frequency, and power factor, and evaluating the stability, reliability, and compatibility of the electrical energy output. Indicators such as voltage stability, frequency stability, and harmonic distortion are calculated to ensure the electrical energy meets the required standards.

By implementing these testing methods and analyzing the data, the performance and quality of wave energy conversion devices can be accurately evaluated. This information is crucial for optimizing the design, operation, and maintenance of these devices, and for promoting the development and utilization of wave energy as a clean and renewable energy source.

2.1. Power performance testing

Power characteristics can reflect the output power response characteristics of wave energy conversion devices under different sea conditions. The main indicators are the power characteristic matrix, conversion efficiency, and annual electricity generation [3]. The power characteristics of wave energy conversion devices are the most important indicators for evaluating the operation of the power generation unit. Through power characteristics, it is possible to assess whether the output power meets the requirements under varying sea conditions, whether the electrical energy meets the grid requirements, and whether the annual electricity generation meets the design needs [4].

2.1.1. Testing principle

To ensure the scientific and rationality of the power characteristic testing method, this experiment is based on the reference of the power characteristic testing technical specification proposed by IEC for wave energy conversion devices. Considering the differences in wave energy resources distribution between China's sea areas and European sea areas, a power testing method suitable for wave energy conversion devices in China is proposed. The testing procedure is shown in Figure 1.

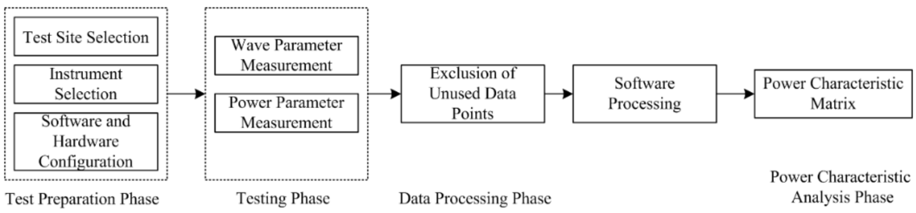

Figure 1: Power characteristic testing process flowchart

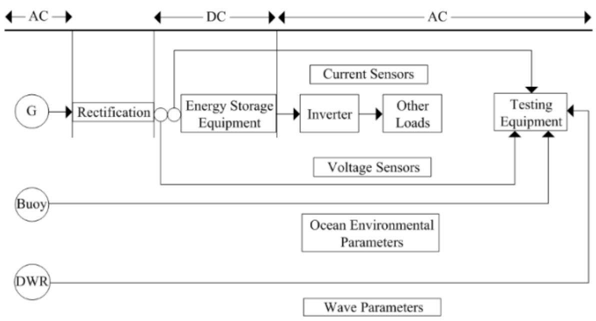

Figure 2: Illustration of the testing system relationships

During the testing process, it is necessary to simultaneously measure the marine environmental parameters in the marine area where the wave energy conversion device is located, as well as the DC voltage and DC current data outputted by the device after passing through the rectifier. The interconnection relationship between the devices and the data acquisition and processing relationship are shown in Figure 2.

2.1.2. Measurement factors

When testing the power characteristics of wave energy conversion devices, it is necessary to synchronously collect marine environmental parameters and power parameters. The main measurement factors/elements include: wave data captured by the wave energy conversion device, including significant wave height, wave period, wave direction, as well as voltage and current parameters rectified by the device after passing through the rectifier. By processing the above data, important power characteristic indicators such as the power characteristic matrix, annual energy production, and output efficiency of the power conversion device can be obtained. The range and accuracy of the measurement factor indicators are shown in Table 1 [5].

Table 1: Measurement factor indicator table

Test Content	Test Factors	Test Range	Test Accuracy
Wave	Wave height	(0.2~20)m	±4%
	Wave period	(2~30)s	±0.5s
	Wave direction	0°~360°	±10°
Power system	Power Voltage	0~1000V	±0.5%RDG ±1mV
	Current	0~500A	
	Frequency	40~70Hz	
	Power factor	0~1	
	Power	/	
	Phase angle	/	
	Harmonics	/	
	Unbalance	/	
	Voltage deviation	/	
	Frequency eviation	/	
	Flicker	/	
	Voltage fluctuation	/	

2.1.3. Measurement locations

The selection of measurement locations is an important step in the preparation phase before testing. The quality of location selection has a significant impact on the accuracy of test results and the representativeness of test data. If the measurement device is located too far from the wave energy conversion device, the measurement data may lose representativeness. However, if the distance is too close, the measurement device may be affected by reflected waves, radiated waves, diffracted waves, and device blockage [6]. Therefore, the specific steps for establishing the measurement location model before conducting sea condition testing are as follows [7]:

1) Collecting historical data from wave energy conversion devices in the target sea area, and creating a wave rise chart for the testing area based on this historical data.

2) Modeling and analyzing environmental factors such as the wind field and water depth in the test area during the testing period. Using the model data to predict wave patterns.

3) Comparing the predicted model with the observed values to determine the final measurement location

2.2. Power quality characteristic testing

2.2.1. Power quality characteristics

The use of poor-quality electrical energy in industrial production can increase power consumption, raise quality assurance costs, increase downtime, and reduce equipment lifespan. Therefore, it is necessary to test the power quality of the generated electrical energy before it is connected to the grid. The connection of substandard electrical energy to the grid can lead to reduced grid stability, voltage imbalance, and uneven distribution of reactive power, ultimately resulting in localized or widespread

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power outages and electrical accidents. Therefore, the testing of power quality in power generation systems is an important part of evaluating their performance. In the process of electrical energy production, power quality refers to the uninterrupted and undisturbed use of electrical energy by users, as well as the quality of electrical energy produced by power systems or electrical energy production equipment. Ideally, the output of electrical energy should be a perfect sine wave. However, in practical systems, various factors can cause deviations from the sine wave, leading to optimization issues in power quality. The testing process of power quality for power systems and the output of electrical energy by power generation equipment is an important step in optimizing power quality.

2.2.2. Measurement principle

The construction process of a power quality characteristic testing system needs to consider the specific power system connection method of the wave energy power generation device, the type of generator set, and the series-parallel connection method, etc. For power quality characteristic testing of a power generation device that only includes one type of power generation, the power quality analyzer can be connected to the DC bus through current sensors and voltage sensors in the shutdown state to obtain power quality data. For generator sets that include multiple types of power generation devices (such as wind-solar complementarity, solar-wave complementarity power generation devices), when measuring the power quality of a specific unit, the output power of different generator sets needs to be measured separately. This means that the output power is directly measured at the output terminals of each generator.

The steps for testing the power quality characteristics are as follows [8]:

1) In the shutdown state, disconnect the DC bus from the inverter and the inverter from the load to ensure that the circuit is not energized. Then, connect the voltage sensors and current sensors to the output terminals of the inverter, and use a multimeter to check for any short circuits between the three-phase busbars.

2) Connecting the voltage sensors and current sensors to the power quality analyzer according to the wiring instructions, ensuring that the phase sequence corresponds correctly.

3) Closing the circuit breakers for the DC bus, inverter, and load, and power on the power quality analyzer. Check if the display screen is normal and if there is signal output from the six acquisition lines.

4) Turning on the inverter and then debugging the power quality analyzer. Selecting the automatic detection test environment, including checking if the wiring, voltage direction, voltage phase sequence, current direction, and current phase sequence are correct. If there are any errors, make the necessary changes in the wiring while the wave energy power generation device is shut down and the inverter is disconnected from the grid.

5) Once the power quality analyzer passes the test environment detection, the wiring work is completed, and the power quality testing can begin. Start recording data when the inverter supplies power to the load, with data recorded every 1 minute.

The recorded data is usually saved in the internal memory of the power quality analyzer. However, due to the limited storage capacity of the memory and the large amount of power data that needs to be recorded daily, the internal storage data of the power quality analyzer needs to be manually copied and transferred to a host computer for further data processing and analysis.

In power quality characteristic testing, accurate measurements need to be made for parameters such as AC root mean square (RMS) value, power, power factor, phase angle, efficiency, voltage and current frequency, and harmonic information of the generator output. The AC RMS value includes the current RMS value (Irms) and voltage RMS value (Urms), and power includes active power, reactive power, and apparent power. The RMS value refers to the AC value that consumes the same amount of DC power as when directly applied to a resistive element, and it represents an equivalent from an energy perspective. The AC voltage RMS value can be calculated using equation (1):

$$U_{rms} = \sqrt{\frac{1}{T}\int_0^T u^2(t)dt} \tag{1}$$

The AC current RMS value can be calculated using equation (2)

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{2}$$

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The active power can be calculated as,

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt \tag{3}$$

The apparent power is calculated as follows:

$$S = U_{rms} I_{rms} \tag{4}$$

The power factor (λ) and phase angle (φ) can be calculated as,

$$\lambda = P / S \tag{5}$$

$$\varphi = \cos^{-1}(\lambda) \tag{6}$$

3. Data Processing

3.1. Power Characteristic Data Processing Method and Analysis

After obtaining the raw measured data, a data processing method is needed to group the large amount of raw data and model the power characteristic matrix and power characteristic curve of the wave energy generation device. In this paper, three methods, namely, the bin method, maximum value grouping method, and maximum probability grouping method, were compared for data processing and modeling, and the advantages and disadvantages of each method were analyzed. The Italian standard document UNI/TS 11300-4 proposes the bin method and applies it in the field of thermal energy calculation, dividing thermal energy data into several bin intervals according to the length of time, and applying corresponding statistical calculation methods within each bin interval. The bin method is also widely used in wind turbine power characteristic analysis to classify and process data. Based on the analysis of the similarities and differences between the power characteristics of wind turbine units and wave energy generation devices, this paper draws on the bin method and makes modifications based on the characteristics of wave energy generation, which are applied in the data processing research of this paper.

In wind turbine power characteristic testing, the IEC standard clearly defines that the bin method classifies wind speed data V_i into certain interval lengths, divides them into intervals, and converts the data within each wind speed interval. Finally, the wind speed data obtained in each bin interval is coupled with the power data to generate the corresponding power characteristic curve, thereby analyzing the power characteristics of the wind turbine unit. When applying the bin method to convert wind speed and power output values, the following equation (7) and (8) are used for processing:

$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{n,i,j} \tag{7}$$

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{n,i,j} \tag{8}$$

Where V_i represents the average wind speed calculated in the *i*-th bin interval, $V_{n,i,j}$ represents the wind speed calculated based on the *j*-th group in the *i*-th bin interval, P_i represents the average output power calculated in the *i*-th bin interval, and $P_{n,i,j}$ represents the output power calculated based on the *j*-th group in the *i*-th bin interval.

Compared to wind energy, natural waves are the superposition of several independent waves with different periods and wave heights. Using only one parameter, such as period or wave height, as the criterion for bin cannot fully analyze the relationship between the significant wave height (H_s), period (T_e), and output power. Therefore, the measured data can be grouped according to the significant wave height and period. In each bin interval, the bin interval length for significant wave height is set to 0.5 meters, and the bin interval length for period is set to 1 second. Therefore, compared to the power characteristic curve obtained by analyzing the wind speed-output power bin method in wind turbine units, the power characteristic analysis of wave energy generation devices focuses on the power characteristic matrix.

3.1.1. Power Characteristic Matrix

The power characteristic matrix can be used to estimate the annual power generation of the wave energy generation device. The power characteristic matrix is generated based on the capture length, and it can reflect the power characteristics of the wave energy generation device itself. The capture length parameter can visually describe the effective utilization length of the device for wave energy and plays a decisive role in evaluating the conversion efficiency of the generation device. Evaluating the power characteristics of wave energy generation devices requires analyzing the standardized output power matrix, and the calculation of the output power matrix must be based on the establishment of the capture length matrix for the generation device.

$$J_n = \frac{\rho g^2}{64\pi} H_{m0n}{}^2 T_{en} \tag{9}$$

J_n represents the wave energy flux in n different time intervals t, in units of W/m, ρ represents the density of seawater, in units of kg/m^3; g represents the local acceleration due to gravity; H_{m0n} represents the significant wave height in n sampling time t, in units of m; Ten represents the wave energy period corresponding to the significant wave height in n sampling time t, in units of s. The average output power of the wave energy generation device in n different time intervals t can be calculated as,

$$P_n = \frac{1}{N}\sum_{k=1}^{N} u_k i_k \times 10^{-3} \tag{10}$$

Where P_n represents the average electrical power output of the generator in the nth time interval t, in units of kW, N represents the total number of samples collected during the time interval t of the device, u_k represents the instantaneous voltage sample value, in units of V, i_k represents the instantaneous current sample value, in units of A; n represents the different time intervals of the Bins method. The calculation of the capture length is

$$L_n = \frac{P_n}{J_n} \tag{11}$$

According to the data processing method, the electrical energy data with a period of seconds is processed into data with a period of half an hour synchronized with the wave data, and singular data such as shutdown without power generation and data anomalies are removed, and finally, the synchronized measurement of wave-electrical parameters is obtained.

3.2. Power quality Analysis Method

The collected electrical energy characteristic data during the testing period is processed and analyzed according to the power quality testing method proposed in the previous section. Based on the evaluation indicators of voltage deviation, frequency deviation, and imbalance, the quality of the electrical energy generated during the testing period is evaluated according to the specified limits in national standards.

3.2.1. Voltage Deviation

Voltage deviation refers to the percentage difference between the actual voltage values at the supply and distribution nodes in the power system and the nominal voltage when the system load or operating mode changes. It can be mathematically expressed as

$$\Delta U = \frac{U_{re} - U_N}{U_N} \times 100\% \tag{12}$$

Where ΔU represents the voltage deviation percentage, U_{re} represents the actual voltage value in the system, in units of kV, U_N represents the nominal voltage of the system, in units of kV.

3.2.2. Frequency Deviation

Frequency deviation refers to the difference between the actual frequency value of the system and the standard frequency value during power system operation. It can be mathematically expressed as

$$\Delta f = f_{re} - f_N \tag{13}$$

Where Δf represents the frequency deviation, in units of Hz, f_{re} represents the actual frequency of the electrical energy, in units of Hz; f_N represents the nominal frequency of the system, in units of Hz.

3.2.3. Imbalance

Imbalance refers to the situation where the three-phase voltages have different amplitudes or phase differences that are not 120°, or both. The imbalance index can be calculated as

$$\varepsilon=\frac{U_1}{U_2}\times 100\% \tag{14}$$

Where U_1 represents the effective value of the actual operating voltage positive sequence component, and U_2 represents the effective value of the actual operating voltage negative sequence component. According to the specifications in national standards for the imbalance of three-phase voltages, the allowable value for the imbalance of the common connection point in the power system is 2%, and it should not exceed 4% for a short period of time. The measured voltage imbalance should be within this range.

3.2.4. Harmonics

Harmonics can be generated in the power grid due to the lack of absolute symmetry in the three-phase power supply, the saturation characteristics of transformers in the transmission and distribution process, or the operation of various thyristor devices or frequency conversion devices. Harmonics can be defined as the electrical quantities with frequencies that are multiples of the fundamental frequency in the current, and they can be obtained by Fourier decomposition of periodic non-sinusoidal signals. The presence of harmonic components in the power grid can be measured using the Total Harmonic Distortion (THD) index. The calculation of harmonic distortion can be expressed as

$$THD_h=\frac{\sqrt{\sum_{h=2}^{M}{U_h}^2}}{U_1}\times 100\% \tag{15}$$

Where THD_h represents the total harmonic distortion of the voltage; U_h represents the root mean square value of each harmonic voltage; U_1 represents the root mean square value of the fundamental voltage; M represents the highest harmonic order within the calculation range, which is determined by the degree of waveform distortion and the accuracy requirements of the analysis, usually taken as M≤50.

According to the specifications in national standards for voltage harmonic limits under normal operating conditions of the power grid, when the nominal voltage of the power grid is 0.38kV, the allowable values for total voltage harmonic distortion are 5%, odd harmonics are 4%, and even harmonics are 2%.

3.2.5. Voltage Fluctuation

Voltage fluctuation refers to the rapid change in the effective value of the voltage in the power grid during normal operation. It is usually caused by non-linear loads, impulsive events, or uneven power distribution. Voltage fluctuation can be represented by the difference between the maximum voltage value $U_{\max}$ and the minimum voltage value $U_{\min}$ during voltage variations. The relative percentage value of ΔU to the system's standard voltage is commonly used to express voltage fluctuation, as shown in (16)

$$d=\frac{U_{\max}-U_{\min}}{U_N}\times 100\% \tag{16}$$

Where $U_{\max}$ represents the maximum value of the voltage during the voltage variation, $U_{\min}$ represents the minimum value of the voltage during the voltage variation, and U_N represents the nominal voltage at this voltage level.

3.3. Uncertainty Analysis

The evaluation and analysis of the operational characteristics of wave energy generation devices during testing require an analysis of the effects of uncertainty and errors in the measurement process. Since uncertainty in the measurement process is often caused by various factors, an assessment of uncertainties of unknown origin is required, which is divided into Type A evaluation and Type B evaluation. Type A evaluation is based on statistical analysis of the measurement, taking into account the effects of various influencing factors based on achieved repeatability. Type B evaluation uses other methods for assessment and can rely on empirical knowledge, providing an approximate estimate. In the data analysis process, uncertainties of both types are calculated in the form of standard deviations. In this section, uncertainty evaluation will be carried out for the measured values of significant wave height, wave energy period, and electrical power. According to the principle of minimum error, both significant wave height and wave energy period are considered as measured parameters. The uncertainty

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components of the measured quantities are converted into uncertainty quantities in the form of sensitivity factors. Based on the specifications in the IEC Wave Energy Converter Field Testing Technical Manual for the different parameter components, the uncertainties of the test parameters and their components are shown in Table 2.

Table 2: Uncertainty Parameter Specification Table

Measurement Parameter	Error Composition	Error Category
Significant Wave Height	Influences from wave measurement devices	B
	Data acquisition system	B
	Wave direction analysis	B
	Variations in significant wave height	A
Energy Period	Influences from wave measurement devices	B
	Data acquisition system	B
	Wave direction analysis	B
	Variations in energy period	A
Output Power Parameter	Current sensors	B
	Voltage sensors	B
	Power transmitters, etc.	B
	Data acquisition system	B
	Variations in electrical power	A

4. Conclusions

In the context of vigorously promoting the utilization and development of ocean energy and with continuous investment of funds in marine renewable energy to support new types of power generation devices, there will be an increasing number of wave energy generation devices being deployed for sea trials and entering the phase of real-sea condition testing and demonstration. This paper conducted research on the comprehensive performance evaluation testing of wave energy generation devices, which includes power characteristic testing and power quality characteristic testing. In the power characteristic testing, the power characteristic matrix of wave energy generation devices was analyzed. In the power quality characteristic testing, evaluation indicators such as voltage deviation, frequency deviation, harmonics, and voltage fluctuation were calculated and analyzed according to national standards. Drawing on the advanced experience of domestic and foreign research institutions in the field testing process and data analysis methods of wave energy generation devices, this paper proposes testing methods for power characteristics and power quality characteristics, providing reference for the performance evaluation system of wave energy generation devices.

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