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A maximum power point tracking algorithm for buoy-rope-drum wave energy converters

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Abstract. The maximum power point tracking control is the key link to improve the energy conversion efficiency of wave energy converters (WEC). This paper presents a novel variable step size Perturb and Observe maximum power point tracking algorithm with a power classification standard for control of a buoy-rope-drum WEC. The algorithm and simulation model of the buoy-rope-drum WEC are presented in details, as well as simulation experiment results. The results show that the algorithm tracks the maximum power point of the WEC fast and accurately.

1. Introduction

Ocean contains abundant wave energy which has a promising prospect to exploit and utilize as a clean renewable energy [1-4]. In order to maximize the energy conversion efficiency of the buoy-rope-drum wave energy converters (WEC), using the maximum power point tracking (MPPT) control strategy is essential [5, 6].

There are many kinds of methods of MPPT control strategy including Perturb and Observe (P&O), Incremental Conductance, Fractional Open-Circuit Voltage, Fuzzy Logic Control, etc. Though the widely applied P&O method has the advantages of having relatively simple structure, less measured parameters and being easy to implement [7], it has the defect of being unable to satisfy the fast tracking speed of the MPPT and the high tracking precision at the same time. What is more, the wave energy is extremely unstable and the wave is nonlinear and stochastic, which makes it harder to track the maximum power point (MPP) of the WEC effectively. In order to overcome these disadvantages and maximize the energy conversion efficiency of the WEC, a novel variable step size P&O MPPT algorithm is presented. Compared with other P&O MPPT algorithms, the new one has a power classification standard and a variable step size standard. The results of simulation experiments show that the variable step size P&O MPPT algorithm tracks the MPP fast and accurately.

2. Buoy-rope-drum WEC simulation model overview

For the sake of testing the performance of the variable step size P&O MPPT algorithm presented in this paper, the buoy-rope-drum WEC simulation model using this algorithm is built in

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MATLAB/Simulink which is shown in figure 1. This model mainly contains the following four modules: buoy hydrodynamic force response module, electric generator module, DC-DC boost converter module and MPPT algorithm module.

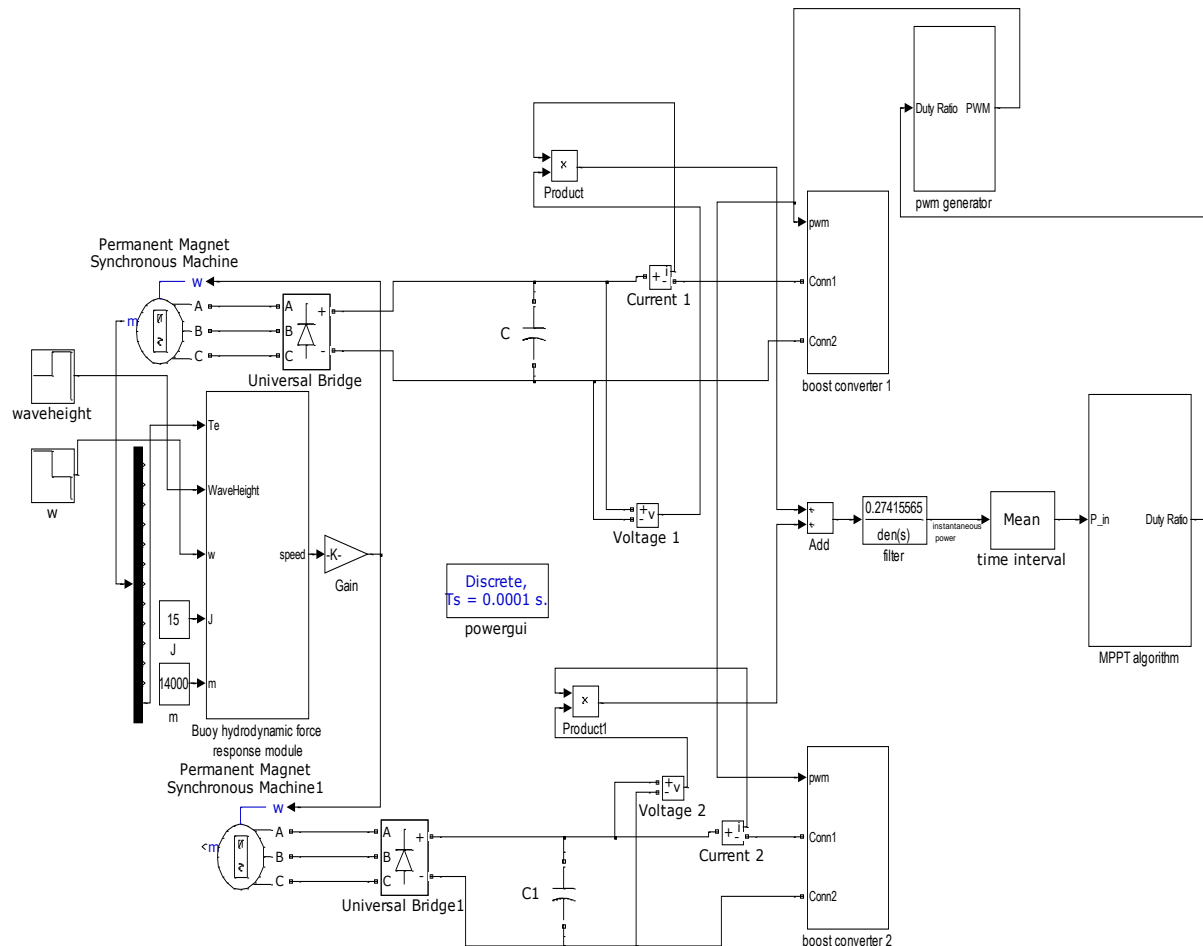


Figure 1. Simulink model of buoy-rope-drum wave energy converters

2.1. Buoy hydrodynamic force response module

In [8], authors derive the hydrodynamic force response equation of the WEC. In order to build the module conveniently and get the motion state of the buoy accurately, the equation is modified as

$$\ddot{x} + \frac{C_1}{m + \frac{J}{r}} \dot{x} + \frac{\gamma A}{m + \frac{J}{r}} x = \frac{\frac{H}{2} e^{-kD} \sqrt{(\gamma A)^2 + (C_1 \omega)^2}}{J} \cos(\omega t + \sigma) - \frac{T_e}{mr + \frac{J}{r}} \quad (1)$$

Where x is the displacement of the buoy, C_1 is the linear friction coefficient of sea water, m is the mass of the WEC, J is the rotational inertia of the drum, r is the radius of the drum, γ is the seawater specific gravity, A is the cross-sectional area of the buoy, H is the significant wave height, k is the wave number, D is the static draft depth of the floating body, ω is the

wave radian frequency and T_e is the electromagnetic torque of the generator.

In real ocean environment, the buoy is affected by the loads of wave, wind and tide. Shandong University tested a buoy-rope-drum WEC in ocean whose buoy diameter is 4.5 m and height is 2 m. In [9], the loads of wave, wind and tide imposed on the WEC tested by Shandong University are analyzed and calculated. The results show that because the size of buoy is relatively small, the values of wind load and tidal load are small leading to little effects on the motion of the buoy. In order to simplify the mathematical model of the buoy motion, equation (1) ignores the effect of loads of wind and tide.

The buoy hydrodynamic force response module is built in MATLAB/Simulink according to the equation above. To accurately simulate the running state of the buoy-rope-drum WEC tested in the ocean before, the parameters of the buoy are set the same as the Shandong University's WEC.

2.2. Electric generator module

In this module, the permanent magnet synchronous generator (PMSG) block whose parameters are as same as the engineering prototype is selected. Because there are two generators in the WEC engineering prototype, two PMSG models are used in the module.

2.3. DC-DC boost converter module

Boost converters have the function of changing the impedance across the dc-link as given in

$$R_{eq} = (1 - D)^2 \cdot R \quad (2)$$

Where D is the boost converter duty ratio and R is the load resistance at the output [10]. In order to realize load matching when the WEC runs in the ocean, the variable step size P&O MPPT algorithm can be used to manipulate the boost converter duty ratio to maximize the output power. The DC-DC boost converter module used in this paper is shown in figure 2.

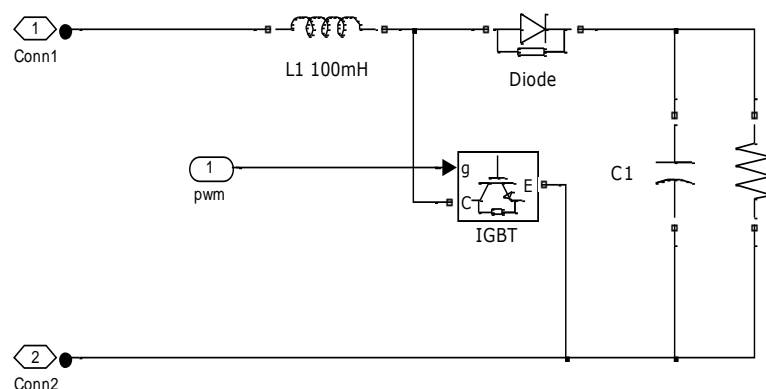


Figure 2. Simulink model of boost converter module

2.4. MPPT algorithm module

The variable step size P&O MPPT algorithm presented in this paper is written in the Embedded MATLAB Function block of Simulink.

3. Variable step size P&O MPPT algorithm

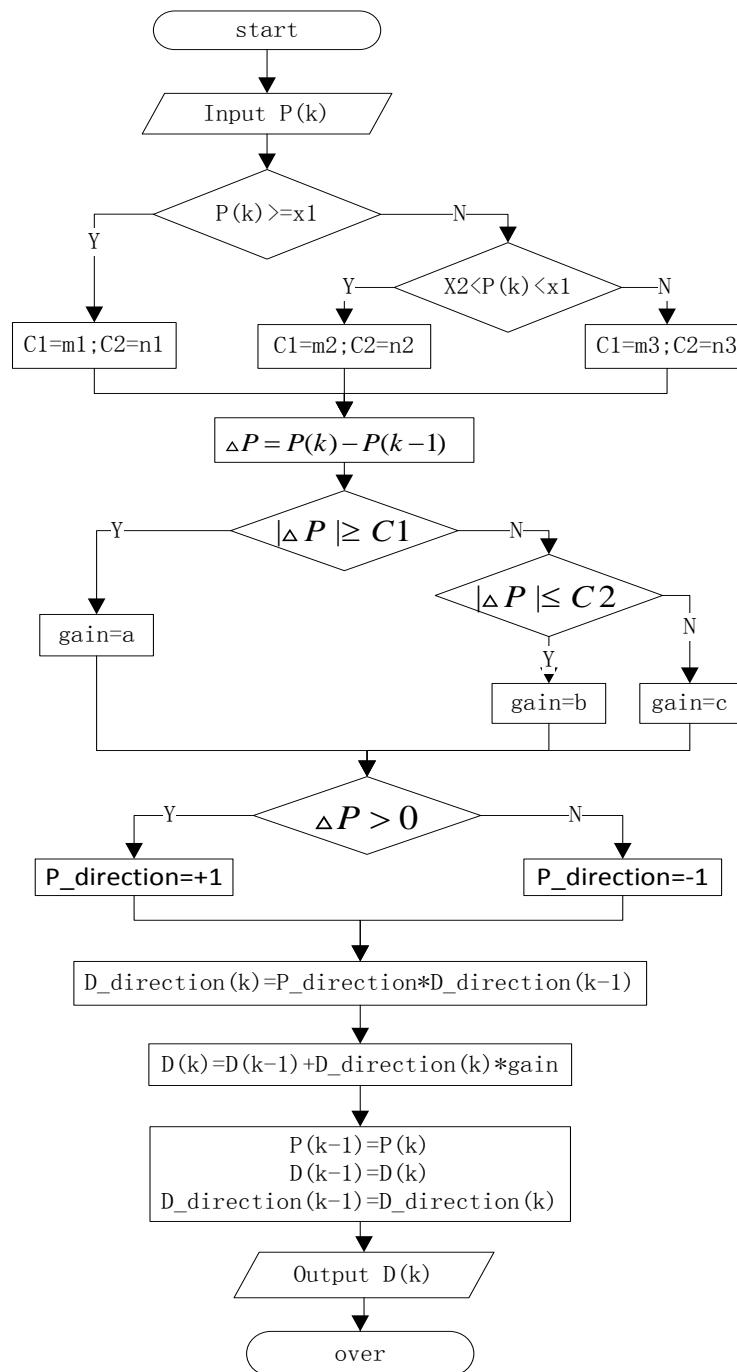


Figure 3. The flowchart of the variable step size P&O MPPT algorithm

Figure 3 shows the flow chart of the variable step size P&O MPPT algorithm. First, the algorithm divides the current average input power (i.e., output power of the WEC), $P(k)$, into different grades which determine the corresponding variable step size criterion, $C1$, $C2$ ($C1 > C2$). Second, the algorithm calculates the difference, ΔP , between $P(k)$ and the average input power from the previous time interval, $P(k-1)$. If $|\Delta P|$ is greater than or equal to $C1$, then the step size, $gain$, is set to a . If $|\Delta P|$ is less than or equal to $C1$, then the step size is set to b , otherwise $gain$ is set to c , where $a > c > b$. If ΔP is positive, $P_direction$ is set to $+1$. The assumption is that the direction of change in

the boost converter duty ratio in last time interval, $D_{\text{direction}}(k-1)$, has increased the power production from the WEC and therefore is left unchanged. On the contrary, if ΔP is negative, $P_{\text{direction}}$ is set to -1, which means the direction of change in the boost converter duty ratio has decreased the power production and will change sign. The product of $P_{\text{direction}}$ and $D_{\text{direction}}(k-1)$ produces the direction of change in the boost converter duty ratio, $D_{\text{direction}}(k)$. The output duty ratio, $D(k)$, is then increased or decreased according to the product of gain and $D_{\text{direction}}(k)$. Executing the algorithm repeatedly will realize maximum power point tracking.

In the algorithm, the interval time, T , the variable step size criterion, $C1$, $C2$, and the step size, gain , are the key parameters which affect the performance of the algorithm significantly. Because the buoy-rope-drum WEC has the characteristics of having large inertia and only producing electric during the upward stroke of the buoy, the interval time, T , over which the input power is averaged and control updates are commanded need to be long enough to wait for the WEC getting into steady state. If T is too short, the algorithm will tune the boost converter duty ratio before the WEC is steady, which will cause misjudgment making it impossible to track the MPP. Wave energy is proportional to the product of the wave height squared and the wave period [11] and wave state is significantly different at different times, which makes the energy carried by different waves very different. If the input power is not classified before the step size is determined, the algorithm will only realize the MPPT in some wave conditions. In order to make further improvement on the performance of the algorithm used in the simulation experiments, $P(k)$ is divided into six grades. The value of the step size affects the tracking speed and the steady state tracking precision of the algorithm. When the WEC works far away from the maximum power point, larger steps allow the algorithm to close more quickly on it. However, when the WEC works near the MPP, smaller steps would avoid excessive dithering and decrease energy loss. Determining the step size reasonably would improve the efficiency and the stability of the algorithm. In this paper, the parameters of the algorithm are determined after extensive test optimization using the buoy-rope-drum WEC simulation model presented above. Finally, in the algorithm, $T=50\text{s}$, $a=0.05$, $b=0.01$, $c=0.03$ and $P(k)$ is divided in 6 grades where $P(k) \geq 7000\text{w}$, $5500\text{w} \leq P(k) < 7000\text{w}$, $4000\text{w} \leq P(k) < 5500\text{w}$, $2500\text{w} \leq P(k) < 4000\text{w}$, $1000\text{w} \leq P(k) < 2500\text{w}$, $P(k) < 1000\text{w}$.

4. Simulation experimental results and analysis

4.1. Simulation experimental results and analysis of the buoy-rope-drum WEC with resistive loads

The purpose of the simulation experiment is to confirm the maximum power point of the WEC at different wave conditions and provide the control group for subsequent experiments. First, the boost converter module in figure.1 is replaced by resistive loads, then the WEC operates under 12 wave conditions respectively where the resistive loads increase from 5Ω to 50Ω with 5Ω every increase. The experimental results are shown in figure.4. The wave heights of the first group's three wave conditions are all 0.5m and the wave periods are 5.5, 6, 6.5s respectively. The wave heights of the other three groups are 1, 1.5, 2m with periods as same as the group one. As shown in figure 4, the output power curves of the WEC are unimodal curves and the MPPs at different wave conditions are acquired.

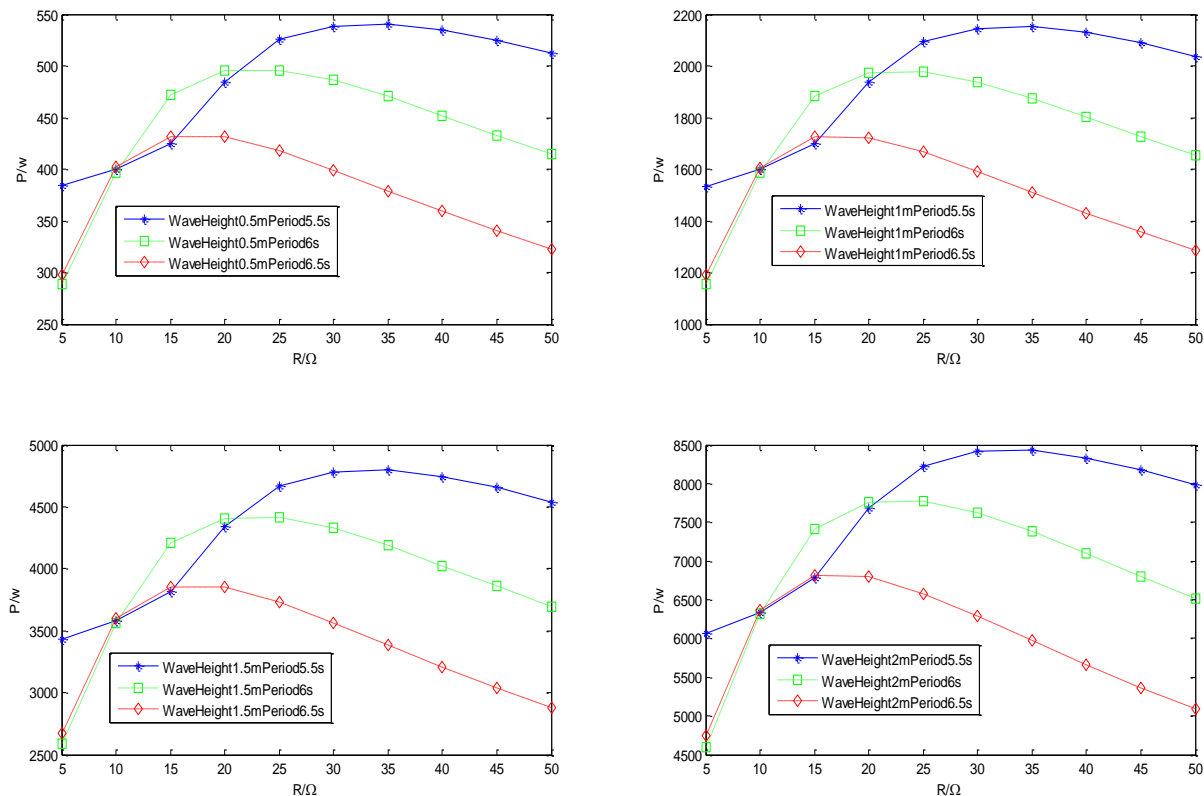


Figure 4. The output power curves of buoy-rope-drum wave energy converters in 12 different wave conditions

4.2. Simulation experimental results and analysis of the buoy-rope-drum WEC under MPPT algorithm control

The purpose of this simulation experiment is to testify that the variable step size P&O MPPT algorithm presented in this paper has good steady state tracking precision. The simulation model used in this experiment is shown in figure.1. The steady state output powers of the WEC and the power tracking error rates are obtained in the simulation experiment with the wave conditions as same as the experiment's operated in 4.1. Results are listed and compared with the results of the 4.1 experiment in table1. As shown in table1, the power tracking error rates are all less than 5%, which means the MPPT algorithm tracks the MPP nicely. There are two main reasons causing the existence of the power tracking error. First, the power electronic devices chosen for the simulation model like IGBTs, diodes are not ideal components so the forward voltage drop and the switching loss exist. Second, even if the novel variable step size P&O MPPT algorithm is used, the power oscillation near the MPP cannot be eliminated completely leading to the power waste. The power oscillation under steady state is the inherent defect of P&O methods which cannot be avoided.

Table 1. The output power and power tracking error rates of buoy-rope-drum wave energy converters in different wave conditions

Wave conditions (Wave height, H, Wave period, T,)	Maximum power point values/W	Steady state output power of WEC under MPPT control/W	power tracking error rates
H=2 m; T=5.5s	8430	8150	3.32%
H=2 m; T=6s	7780	7640	1.80%

H=2 m; T=6.5s	6810	6700	1.62%
H=1.5m;T=5.5s	4795	4620	3.65%
H=1.5m;T=6s	4415	4390	0.57%
H=1.5m;T=6.5s	3855	3800	1.43%
H=1 m; T=5.5s	2152	2055	4.51%
H=1 m; T=6s	1977	1930	2.38%
H=1 m; T=6.5s	1725	1700	1.45%
H=0.5m;T=5.5s	540.5	516	4.53%
H=0.5m; T=6s	496	490	1.21%
H=0.5m;T=6.5s	432	423	2.08%

4.3. Simulation experimental results and analysis of the buoy-rope-drum WEC under MPPT algorithm control with changing wave conditions

This experiment is to testify that the variable step size P&O MPPT algorithm can track the MPP fast and accurately under changing wave conditions. The simulation model used in this experiment is shown in figure 1. The experimental process is divided into three stages. First, the experiment is run with wave height set to 1.5m and wave period set to 5.5s. When simulation time is 300s, the wave height is adjusted to 2m and wave period to 6s. Keep this wave condition until simulation time is 600s then the wave height and wave period are adjusted to 1m and 6.5s respectively. The steady state output powers at different stages are listed in table 2 and the instantaneous output power curve is shown in figure 5. As observed, the algorithm tracks the maximum power points of different stages fast and accurately.

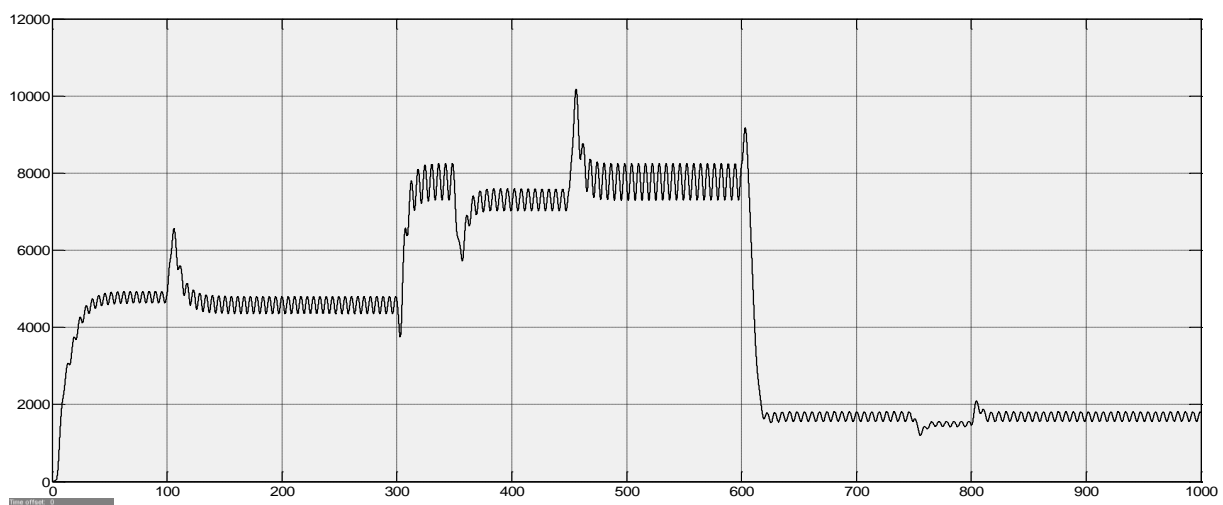


Figure 5. The instantaneous output power curve of the buoy-rope-drum wave energy converter

Table 2. The output power and power tracking error rates of buoy-rope-drum wave energy converters in changing wave conditions

Stages	Maximum power point values/W	Steady state output power of WEC under MPPT control/W	power tracking error rates
Stage 1: H=1.5m; T=5.5s	4795	4593	4.21%
Stage 2: H=2 m; T=6s	7780	7770	0.13%
Stage 3: H=1 m; T=6.5s	1725	1690	2.03%

5. Conclusions

This paper presents a novel variable step size P&O MPPT algorithm designed to maximize the energy conversion efficiency of the buoy-rope-drum wave energy converter. Simulation model of the WEC is built in MATLAB/Simulink environment and simulation experiments are done. The results show that the algorithm can track the maximum power point fast and accurately and maximize the output power during the whole operating process. The power classification standard and variable step size standard introduced in the algorithm enhance the robustness and adaptability of the algorithm significantly relieving the contradiction of the tracking speed and the tracking precision of the algorithm. This investigation also provides theoretical direction for the design of the DC-DC boost converters and the power control system of the buoy-rope-drum WEC.

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