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Improved climbing algorithm with variable step size in tidal energy Application of maximum power tracking control technique for power generation system

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Improved climbing algorithm with variable step size in tidal energy Application of maximum power tracking control technique for power generation system

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Abstract. In the context of carbon neutral carbon peak, in order to cope with climate change caused by environmental pollution and energy shortage caused by excessive use of fossil energy, the vigorous development of clean, low-carbon, and efficient renewable energy has become a major strategic direction. The development and utilization of tidal energy in China is still a certain gap with the European powerhouse, the efficiency of tidal energy generation at a low flow rate is low and the scale of development and utilization is small. The feasibility of the proposed strategy is verified by simulation analysis, and the results show that the improved variable step climbing algorithm can quickly track the maximum power point and operate stably at this point.

1. Introduction

With the progress of the times and modernization, the energy demand of countries has achieved linear growth. The reserves of traditional fossil energy sources coal, oil, and natural gas are limited and non-renewable, while the human demand for energy is long-lasting. At present, the most important source of energy used by human beings is non-renewable energy, and the three traditional fossil energy sources account for about 90% of total energy consumption, while renewable energy sources account for only about 10% [1]. In 2021 global energy demand increased by 4.6%, of which the use of all types of fossil energy has increased significantly. According to statistics, for coal alone, the incremental demand is 60% higher than the total incremental demand for all renewable energy sources, resulting in an increase in emissions of nearly 1,500 megatons. In 2021 global coal demand is close to its peak, with coal demand increasing by 4.5%, with China alone accounting for more than 50% of the global coal demand growth. Based on the analysis of China's national situation, China has a large population and poor energy resources but is the first major consumer of energy.

The use of energy resources in China is relatively tight, in the long run, China's fossil energy will be consumed, and the country will face an energy crisis at the same time will also bring serious environmental pollution problems. In order to meet China's economic development at the same time, to greatly reduce the pollution of the environment, reduce the use of the three major fossil energy and other non-renewable energy, the development and use of environmentally friendly, green renewable energy, improve the proportion of clean energy in the total energy consumption, accelerate the development of renewable energy, the implementation of renewable energy alternative action, the development of renewable energy is in a promising strategic opportunity period. From the domestic point of view, China's renewable new energy development is facing unprecedented opportunities, energy transformation speeds up, high-quality leap forward in development is a long way to go. China's carbon dioxide emissions strive to reach the peak by 2030 and strive to achieve carbon neutrality by 2060, which puts forward higher requirements for the development of renewable energy.

With the ocean development strategy and the development of the ocean economy sunrise, countries increase the development and utilization of clean energy such as ocean energy, and the development of renewable energy has become the consensus of mankind. China's main development in clean energy is wind power, photovoltaic, ocean energy, and so on. The earth is known as the water ball, and the earth's water coverage area of 71%, because ocean energy contains huge energy, countries around the world scrambled to invest in the development and utilization of ocean energy research. As an environment-friendly new energy source, the main characteristics of tidal current energy are regular flow direction, accurate prediction, stable energy, and high density. At present, the international tidal current energy generation technology is mainly applied to the high current velocity sea, for China should be developed to adapt to the characteristics of our sea: low current velocity, and many coastal islands. Therefore, the research and development of low-current generator sets will effectively solve the increasingly prominent power supply problems of coastal and islands, and can effectively use tidal currents to provide electricity for the coastal, island, and marine monitoring instruments, which is of great significance to alleviate the energy crisis, mitigate environmental degradation and promote the sustainable development of the marine economy.

Based on the current situation of tidal current resources and sea currents in China and Italy, this paper solves the problem of low efficiency of power generation at low currents, aims to improve the level of low-current power generation technology and expand the development scale, and lays a solid foundation for the further development of low-current tidal current energy generation technology. Most of the existing tidal current power generation technologies in China are developed for high current velocity waters, and the research in this paper fills the problem of insufficient utilization of tidal current energy. The high-efficiency and high-reliability tidal power generation technology at low current velocity responds to the national call for green energy transformation, and at the same time consolidates and enhances the innovation and competitiveness of the renewable energy industry.

2. General scheme of the tidal power generation system

The utilization of tidal energy has realized the trend of continuous expansion of the development scale, and with the continuous improvement of the technology level, it is the current priority to improve the indicators of tidal energy power generation technology. The power utilization coefficient of tidal energy is a function of the leaf tip speed ratio. From this, we can get that the three values of flow velocity v, leaf tip speed ratio, and maximum tidal energy utilization coefficient are corresponding, and the leaf tip speed ratio must be controlled as the optimal value if we want to obtain the maximum power of tidal energy. At the same time, in order to achieve the normal use of the load, the frequency and amplitude of the emitted power should be stabilized through rectification and inversion [2].

The mechanical power captured by the impeller in the tide is:

$$P = \frac{1}{2}\rho\pi R^2 v^3 C_P = \frac{1}{2}\rho v^3 S C_P \tag{1}$$

The equation for the leaf tip speed ratio is:

$$\lambda = \frac{R\omega}{v} = \frac{\pi n D}{60v} \tag{2}$$

When working in the flow region below the rated flow rate, in order to obtain the maximum tidal energy, the energy gain coefficient of the impeller is a function of the blade tip speed ratio, so that the value of the energy gain coefficient at a fixed pitch angle is optimal. And the power characteristic curve can be obtained, as shown in Figure 1.

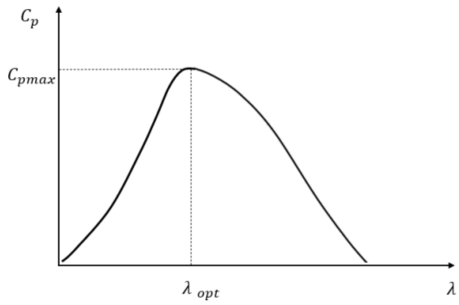

Figure 1. C_P-λ-Characteristic curve of fixed-pitch tidal power generator set

The main principle is that the generator shaft of the generator set is directly connected to the impeller, and the current acts on the impeller to make it rotate, so the rotor speed changes with the current speed and the frequency of the alternating current also changes. The tidal power generation system consists of four main components: impeller, generator, power conversion, and processing unit, and control system. The working principle diagram of the system is shown in Figure 2.

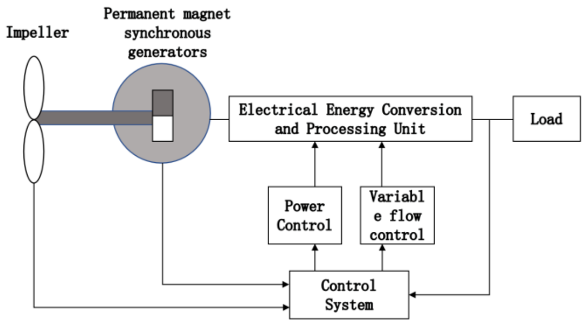

Figure 2. Working principle diagram of the tidal energy generation system

3. System control scheme

The tidal energy generator set is an independent power generation system, and a well-designed control system determines the efficiency of power generation. The control system will realize the control of unit start-up, operation, maximum power tracking, full-load power generation, protection, etc. The system control principle diagram is shown in Figure 3. The control loop acts as the information processing center of the whole system as well as carries out command sending and regulates the normal operation of each part of the system [3]. In the process of energy conversion and energy transformation, the alternating current (AC) output from the generator is converted into direct current (DC) and then into frequency alternating current (AC) for use by the load through the rectifier circuit, filter circuit, and inverter circuit.

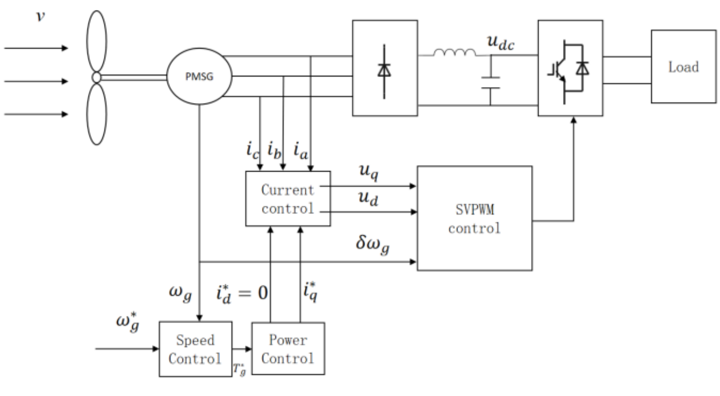

Figure 3. System control schematic

In achieving the maximum power tracking control, it is known from the C_p-λcurve that the control of the power can be achieved by changing the PMG speed. In this paper, a power control strategy based on the load regulation method is used to control the generator speed size to achieve output power control by changing the output load size [4-5]. In the control and regulation process, the double closed-loop control method of the current inner loop and speed outer loop will be realized. Determination of speed external loop is given amount: Under the determination of the current flow rate, according to the generator output power and speed, on the basis of this speed size, up and down fine adjustment is made, the output power value is recorded, until getting a certain speed output power under the maximum value, this generator speed is determined as the speed external loop given value. The output of the current and speed double closed-loop control enters the SVPWM control area, and by changing the duty cycle of the PWM signal, it realizes the control of the load size and makes the generator work at the predetermined speed.

Permanent magnet generator torque equation:

$$T_e = 1.5p\left[\delta \cdot i_q + \left(L_d - L_q\right)i_d i_q\right] \tag{3}$$

When $i_d = 0$ there are:

$$T_e = 1.5p\delta \cdot i_q \tag{4}$$

When $i_d = 0$, the electromagnetic torque of the generator T_e has the above relationship with the current component i_q. The magnitude of the generator torque is determined by component ii of the q-axis as long as $i_d = 0$ is maintained during system operation i_q the stator current is perpendicular to the d-axis. The value of the q-axis component i_q of the current is provided by the speed regulator. The current q-axis and d-axis need to be decoupled for control purposes and pre-voltage compensation is applied to u_d and u_q.

$$\begin{cases} u_d = \omega_g L_q i_q + \dot{u}_d \\ u_q = -\omega_g L_d i_d + \delta\omega_g + \dot{u}_q \end{cases} \tag{5}$$

Magnetic chain equation:

$$\begin{cases} \psi_d = -L_d i_d + \delta \\ \psi_q = -L_q i_q \end{cases} \tag{6}$$

The union of (5) and (6) yields:

$$\begin{cases} \dot{u}_d = \left(\frac{d}{dt}L_d + R_s\right) i_d \\ \dot{u}_q = \left(\frac{d}{dt}L_q + R_s\right) i_q \end{cases} \tag{7}$$

From the above equation, $\dot{u}_d$ and $\dot{u}_q$ are linearly related to $i_d$and i_q respectively. After compensation, the voltage components u_d and u_q are obtained, and then the Park inverse transform is performed to obtain u_α and u_β under the ab axis system as the input quantity for SVPWM vector operation, and finally the trigger pulse for controlling the IGBT switch in the inverter circuit is obtained. The duty cycle of the PWM signal is obtained by the time of IGBT operation, which results in different variable power loads at different duty cycles. In general, the maximum power tracking control in this paper is based on the regulation control of variable power load, which controls the generator speed to match the different water flow rates by adjusting the size of the load to induce the power generation system to work at the maximum power point all the time under different flow rates.

4. MPPT tracking control method

4.1. Variable step length hill-climbing search method

In the traditional climbing search algorithm with a fixed step size, the selection of a fixed step size will directly affect the effect of MPPT. Initially, when the step size is set small, it can achieve high precision control purpose, but achieve MPPT response slowly; when the step size is set large, it will affect its control accuracy, and variable step size can improve the system's response speed and control accuracy [6].

The implementation process of the variable step climbing algorithm and fixed step climbing algorithm is basically the same principle. At the beginning of the system operation, the system first searches and advances with large step lengths, tracking at the fastest speed to near the maximum power point, and then searches and advances with more accurate small step lengths near the maximum power point until the system runs stably with maximum power output. There are many methods to find the extreme value of the function [7], and the iterative algorithm is improved not only to achieve good results but also widely used:

$$D_{n+1} = D_n + \Delta D_{n+1} = D_n + a_n \cdot g_n \tag{8}$$

$$a_n = \begin{cases} K; \dfrac{\Delta P_n}{\Delta \omega_n} \geq \varepsilon \\ 0; \dfrac{\Delta P_n}{\Delta \omega_n} < \varepsilon \end{cases} \tag{9}$$

$$g_n = g(\omega_n) = \left.\frac{dP}{d\omega}\right|_{\omega=\omega_n} \approx \left.\frac{\Delta P_n}{\Delta \omega_n}\right|_{\omega=\omega_n} \tag{10}$$

where a_n is the perturbation factor; and k is a non-negative constant.

Equation (9) enables the control of the perturbation, and the size of the value of ε determines the speed as well as the accuracy of the perturbation. The process of implementing this control algorithm is as follows:

(1) Initialization: first the initial value of the sampled motor speed as well as the current and voltage values is detected, then the initial generator output power P_0 reference value is calculated, n = 0 and $\Delta D_{n+1} \neq 0$ are set, and the target duty cycle for the next cycle is calculated according to Equation (8).

(2) For the nth perturbation, the output power and motor speed of the two adjacent perturbations are differenced to obtain ΔP_n and $\Delta \omega_n$, and the value of a_n is determined by Equation (9).

(3) The selection of the disturbance direction is the same as the fixed-step hill climb method.

(4) The above steps are run cyclically until the power generation system operates at the maximum power point.

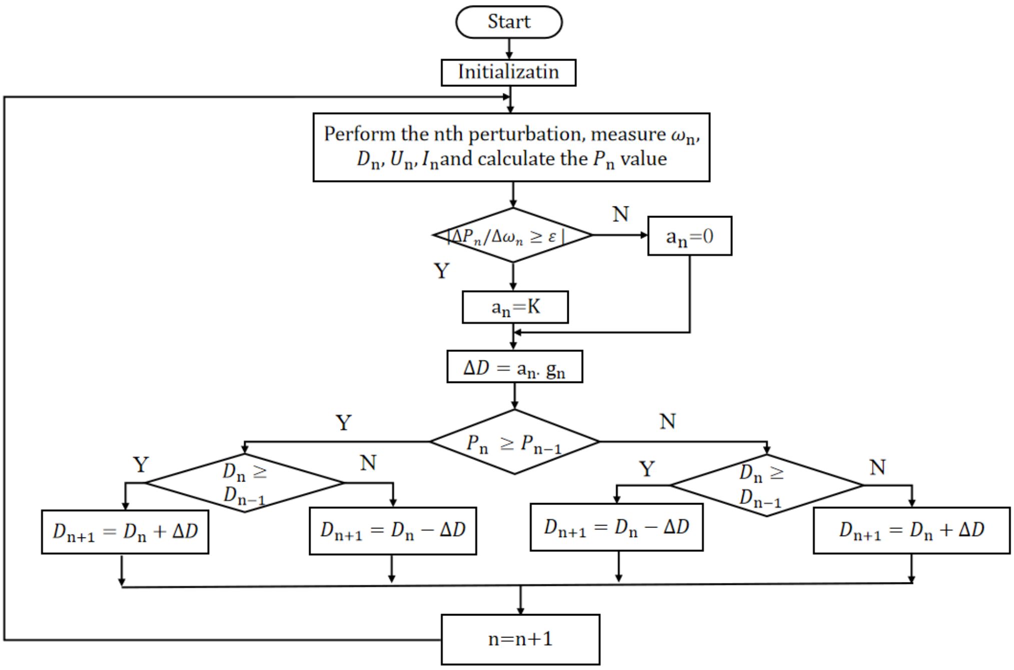

Figure 4. Flowchart of variable step length hill climbing algorithm

From the above algorithm implementation process, it is clear that the slope of the $P-\omega$ curve, the value of $\Delta P_n/\Delta\omega_n$, affects the perturbation step of the duty cycle. When the working point of the system is far from the maximum power point, the $P-\omega$ curve shows that the $\Delta P_n/\Delta\omega_n$ is relatively large, so the duty cycle is scrambled in larger steps; with the search operation system will tend to run towards the maximum power point, at this time the slope of the $P-\omega$ curve gradually becomes smaller, that is, the $\Delta P_n/\Delta\omega_n$ gradually becomes smaller, so the scrambling step of the duty cycle becomes smaller. After applying the variable step control algorithm to this tidal power generation system, the system will operate with a larger step to search for advancement at the beginning of the operation, and a smaller step to search for advancement near the maximum power point, and eventually, the system will tend to stabilize at the MPP. The control algorithm flow chart is shown in Figure 4.

4.2. Improved control strategy of variable step length hill climbing algorithm
In this paper, the Boost converter is used as the key device for power control of the tidal energy generation system, and the system is finally improved based on a variable step length hill climbing algorithm design in order to realize the maximum power tracking control [8-10]. System operation at the beginning of the first large step to search forward to the fastest speed tracking operation to the maximum power point near, in order to avoid close to the best point when the perturbation step is too small and cycle search slow, the system initially run with variable step algorithm, when $\Delta P_n/\Delta\omega_n \leq \varepsilon_1$, $\Delta P_n/\Delta\omega_n \geq \varepsilon_2$ and the output power difference $\Delta P < 0$, the next step operation when the step size is set to half of the step size of the previous cycle, when $\Delta P_n/\Delta\omega_n \leq \varepsilon_2$stop perturbation, so as to cycle operation until system to the maximum power output, the algorithm flow chart is shown in Figure 5.

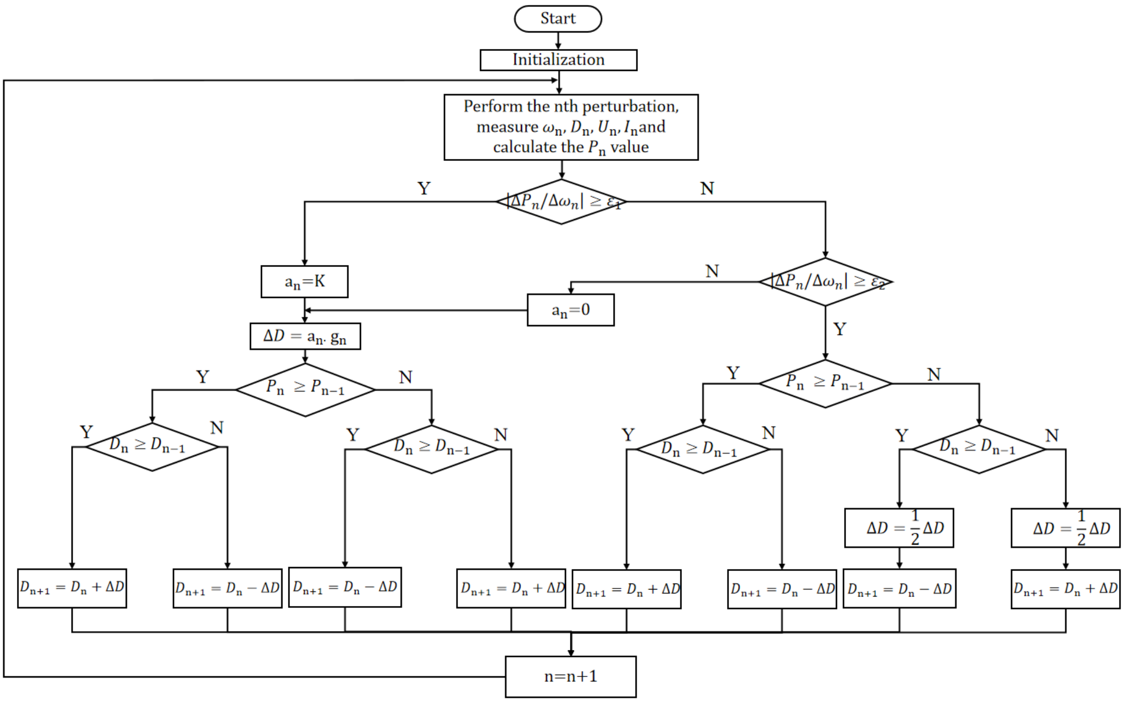

Figure 5. Flow chart of the improved variable step climbing method

5. Direct-drive permanent magnet tidal power generation system modeling and simulation experiments

5.1. Overall simulation model of the tidal power generation system
The simulation model of the permanent magnet direct-drive tidal power generation system is shown in

Figure 6. The whole simulation system includes: an impeller module, permanent magnet generator module, control module, MPPT control module, etc. The simulation parameters are set as shown in Table 1.

Table 1. Main parameters of the model

Name	Parameters
Stator phase resistance (Ω)	0.88
Stator winding inductance (mH)	7
Rotational inertia (kg· m^2)	$8*10^{-4}$
Impeller radius (m)	0.7
polar logarithm	60

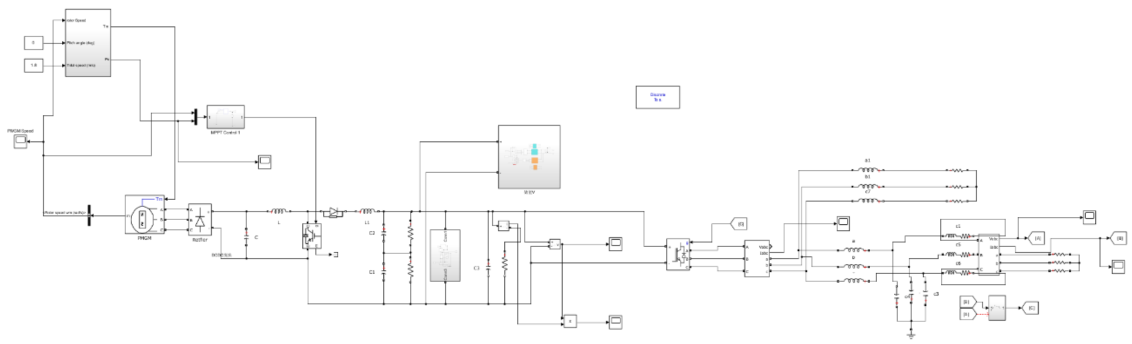

Figure 6. Simulation model of permanent magnet direct-drive tidal power generation system with maximum power tracking control

5.2. Simulation comparison experiment

The tidal flow rate is set to step flow rate for 3s, where the flow rate is 1.6 m/s for 0 — 1.2 s and 1.8 m/s for 1.2 — 3 s. The simulation curves at this tidal flow rate are shown in Figure 7. The initial disturbance step is set to 0.1 and the initial duty cycle is set to 0.25. Through the analysis of simulation results, the tracking effect of the two implemented MPPT, the improved variable step climbing search method and the variable step climbing search method, is compared to analyze the control effect of the two control strategies. The comparison graphs of the simulation results are shown in Figure 8 to Figure 10.

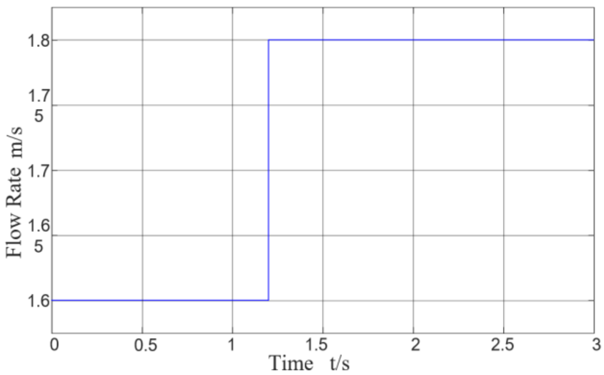

Figure 7. Schematic diagram of a step change of tidal current velocity

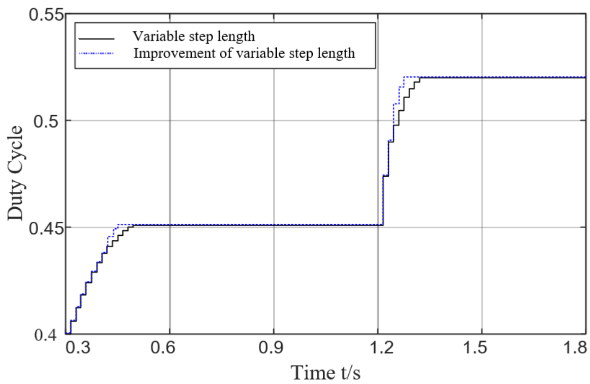

Figure 8. Duty Cycle Simulation Comparison Chart

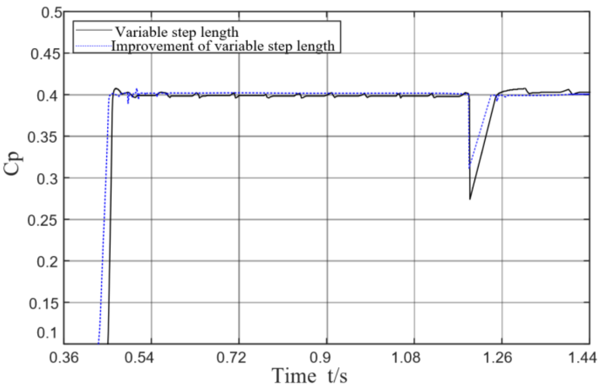

Figure 9. Comparison of simulation results of tidal energy utilization coefficient

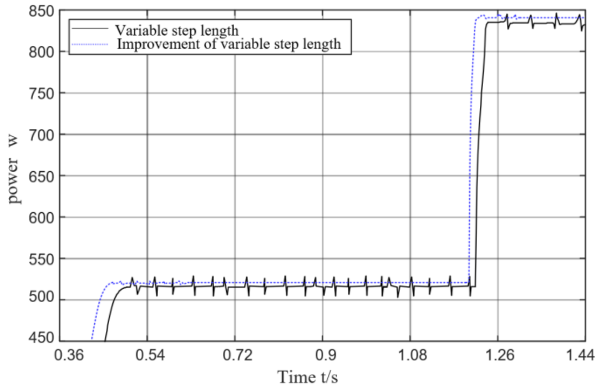

Figure 10. Output power simulation comparison chart

The simulation results from Figure 8 to Figure 10 show that: both algorithms can achieve the maximum power tracking of the tidal power generation system, the perturbation steps of both algorithms are the same before 0.42 s, and the improved variable step algorithm gives priority to tracking to the maximum power point after 0.42 s; the simulation results after 1.2 s are similar to those before 1.2 s, and the improved variable step algorithm takes less time than the variable step algorithm to track to the maximum power. The simulation results after 1.2 s are similar to those before 1.2 s. From the output power simulation graph, we can see that the time to achieve MPP and the stability of the output power of the improved variable step algorithm are significantly improved compared with the variable step algorithm, and the average output power value of the improved variable step algorithm is slightly larger than the output power value of the variable step algorithm.

Through the simulation comparison, we can get that the improved variable step algorithm can track to the maximum power point at the fastest speed and operate stably at the maximum power point, which indicates that the improved variable step algorithm is effective and superior to the variable step algorithm.

5.3. Simulation results at different flow rates

In order to verify the effectiveness of the designed maximum power tracking control algorithm and the performance of the tidal energy generation system, the system with maximum power tracking (improved variable step climbing search algorithm) is compared with the system without maximum power tracking control by using a fixed flow velocity model, a measured flow velocity model for flow simulation, and a comparative study and analysis. The simulation results are analyzed to compare the effects, including the comparative analysis of pair values and captured energy at rated flow velocity; the effect of maximum power curve tracking at actual tidal flow velocity; and the effect of unit power output when the tidal flow velocity is greater than the rated flow velocity, so as to verify the superiority and effectiveness of the proposed control strategy.

5.3.1. Simulation results at a fixed flow rate

Firstly, the control effect of the improved variable-step algorithm is verified at a fixed flow rate. The input flow velocity is 1.8 m/s, and the system with maximum power tracking (improved variable step length hill-climbing search algorithm) and the system without maximum power tracking control are simulated separately, and the following simulation comparison graphs are obtained.

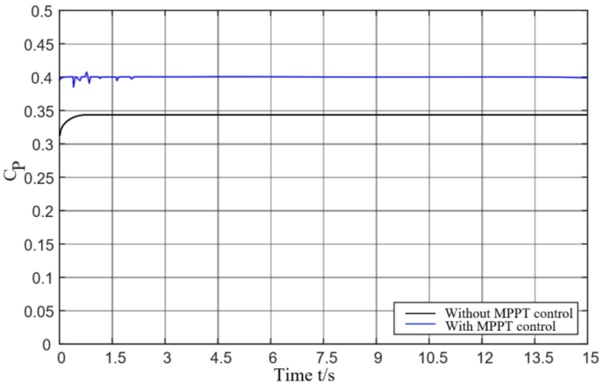

Figure 11. Simulation comparison of tidal energy utilization coefficient under fixed flow rate

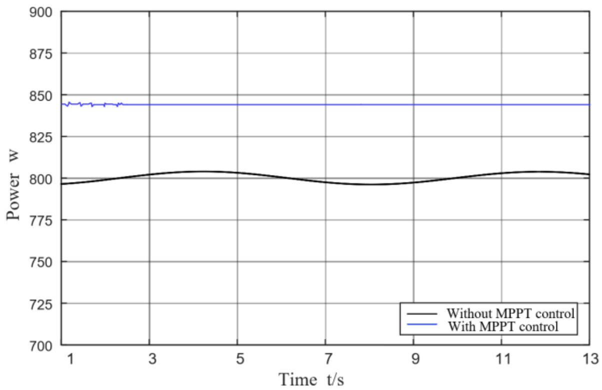

Figure 12. Comparison of output power simulation under fixed flow rate

Figure 11 shows that the C_p value of the tidal energy utilization coefficient is 0.4 for the improved variable step climbing search algorithm control operation, and the C_p value of the tidal energy utilization coefficient is 0.34 without the maximum power tracking control. The output power of the system with MPPT is about 840 W and the output power of the system without MPPT is about 800 W. The output power of the system with MPPT is obviously larger than that of the system without MPPT, and the waveform of the output power of the system with MPPT is much smoother than that of the system without MPPT. The waveform of the output power with the MPPT system is much smoother than that without the MPPT system.

The power factor of the system controlled by PPT is the best power factor of the system, and the output power is the rated power; the power factor of the system without MPPT control is less than the best power factor of the system, and the output power is less than the rated power.

5.3.2. Simulation results under the measured flow rate

The tidal current velocity is affected by many factors, so it is necessary to consider all factors in the modeling process. In order to make the simulation more accurate and realistic, the tidal velocity model is fitted with the measured tidal velocity as the input model of tidal velocity, as shown in Figure 13, and the system parameters are simulated under the measured velocity. The maximum value of input velocity is 1.87 m/s, the minimum value is 1.58 m/s, and the average value is 1.7 m/s. The simulation time is set to 50 s, and the simulation comparison graphs of Figure 14 and Figure 15 are obtained through simulation.

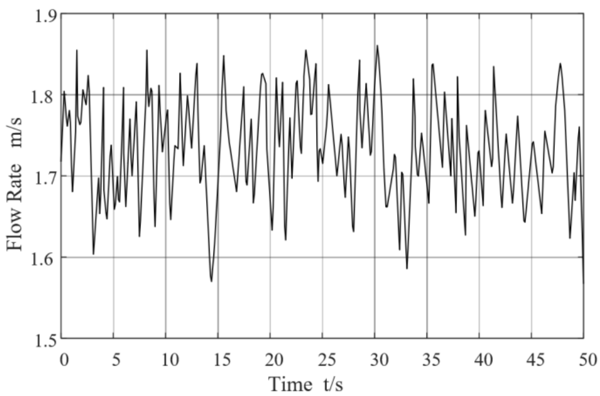

Figure 13. Graph of the tidal flow rate signal input to the system

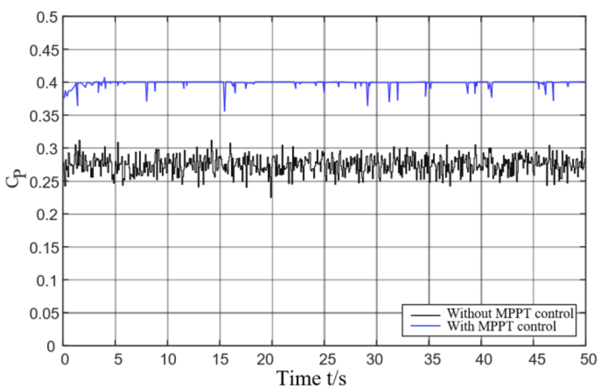

Figure 14. Simulation comparison of tidal energy utilization coefficient under actual measured flow rate

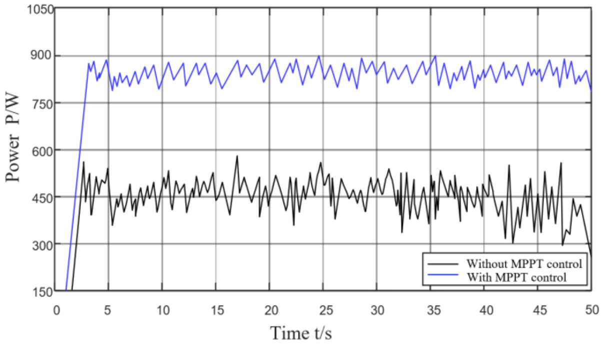

Figure 15. Simulation comparison of output power under actual measured flow rate

As can be seen from Figure 14, there is a significant difference between the tidal energy utilization coefficients with and without the MPPT control system when the tidal current velocity signal is the measured velocity signal. The C_p value of the tidal energy generator set with MPPT control is basically stable at 0.4, which is less affected by the change of flow velocity. When the flow speed is less than 1.8 m/s, the C_p value is basically kept at 0.4, so that the unit can capture the tidal energy to the maximum extent; when the flow speed is greater than 1.8 m/s, the energy capture is reduced by lowering the C_p value to ensure the safe and stable operation of the unit. The C_p value of the unit without MPPT control is greatly affected by the flow rate, and the size of C_p value is 0.25 — 0.3, which basically changes with the size of the flow rate.

From Figure 15, it can be seen that the average output power of the system with MPPT is about 800 W and the average output power of the system without MPPT is about 450 W, and the power captured by the system with MPPT is significantly larger than that captured by the system without MPPT. From the above simulation results and analysis, it can be concluded that the unit can operate normally under the actual tidal flow rate and achieve the expected effect, and realize the purpose of maximum power tracking, which also verifies the rationality of the proposed strategy.

6. Conclusion

In order to solve the problem of coastal and island power supply, the development of low-current tidal energy resources has become the focus and difficulty of research. The problems of difficult operation at low current speed, low energy conversion efficiency, and poor system reliability are holding back the commercialization process of horizontal axis tidal energy units in China. In this paper, we mainly study how to achieve the maximum power capture at a low flow rate, adopt the horizontal axis direct-drive permanent magnet tidal power generator set as the research object, select the hill climbing search algorithm to realize the MPPT control, and make the targeted improvement of this algorithm, and analyze the system modeling and simulation results to verify the effectiveness and superiority of the improved algorithm. The simulation model of each module of the system is built using Matlab/Simulink, and each model forms a complete simulation model of the power generation system for simulation comparison and analysis, which verifies that the proposed improved variable-step hill-climbing search algorithm meets the design requirements and achieves the maximum value of tidal energy capture in the shortest time and stable operation at the maximum power The operation is stable at the maximum power point.

Acknowledgments

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