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Article

Research on Stable Power Generation Technology of Wave Energy

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Abstract: To implement China's maritime power strategy, the development and utilization of wave energy technology has progressed rapidly. Among these, hydraulic wave energy power generation technology holds advantages for large-scale development. However, this technology still faces the issue of discontinuous power output, making the electricity difficult to utilize. To address this, a hydraulic system energy storage and energy conversion control model was constructed. Analysis revealed that the fundamental reason for the discontinuous total power generation under the current hydraulic autonomous control valve method is that the generator's start and stop times are not adjusted in real-time according to the current wave energy size, failing to utilize the energy storage capacity of the hydraulic system. A method was proposed to predict wave energy in real-time and dynamically calculate the generator's start-stop pressure setpoints and operation times. Through simulation experiments, the number of interruptions in wave energy power generation was significantly reduced, and the fluctuation amplitude decreased, achieving continuous and stable power output. This lays a solid foundation for subsequent electrical energy conversion.

Keywords: wave energy; accumulator; control optimization; real time prediction; power generation waveform.

1. Introduction

Ocean energy is the renewable natural energy stored in the ocean. In addition to tidal energy, wave energy, tidal/current energy, temperature difference energy, and salinity difference energy, it also includes wind energy above the ocean and ocean biomass energy, etc[1-3]. Except for tidal energy and current energy, which are derived from the gravitational effects of the sun and the moon on the earth, the other types of energy mainly come from solar radiation. The definition of ocean energy [4] is: energy carriers in the form of seawater, existing in the form of tidal energy, wave energy, tidal/current energy, temperature difference energy, and salinity difference energy through tides, waves, sea currents/tides, temperature differences, and salinity gradients. According to its form of existence, ocean energy can be divided into mechanical energy, thermal energy, and chemical energy. Among them, tidal energy, current energy, and wave energy are mechanical energy, seawater temperature difference energy is thermal energy, and seawater salinity difference energy is

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chemical energy. According to the stability of the energy obtained, ocean energy can be divided into: relatively stable ocean energy, such as temperature difference energy, salinity difference energy, and current energy; unstable ocean energy, such as wave energy. Among these, tidal energy and wave energy are the two with the highest technological maturity[5]. According to the level classification (9 stages) in the research report of IRENA (International Renewable Energy Agency), the technological maturity of tidal energy can reach levels 7-8, and the technological maturity of wave energy is about levels 6-7.

According to surveys, there are 489 inhabited islands in China, and the vast majority of these islands face varying degrees of power shortages. The production and living electricity is extremely tense, which seriously restricts the economic development of the islands and the improvement of the lives of the island residents[6]. At present, the energy utilization methods of China's islands mainly rely on the supply of conventional energy from the mainland, which mainly includes two ways: direct power supply through the laying of submarine cables and diesel power generation. The vast majority of inhabited islands do not have a continuous power supply. China has abundant ocean energy resources, which have the advantages of being renewable, clean, zero-carbon emission, and not occupying scarce land resources. The development process has no energy loss and waste emission, and it is one of the important measures to alleviate the insufficient power supply of China's islands. It is necessary to play the advantages of marine resources, use local materials, and develop and utilize marine renewable energy to provide energy and fresh water for the economic development of coastal areas, the lives of island residents, and national defense construction.

At present, more than ten research institutes and universities in China are conducting research and development on wave energy conversion device technology. The Guangzhou Institute of Energy Conversion of the Chinese Academy of Sciences and other units have a history of more than 30 years of wave energy research and development[7-10]. China has made certain breakthroughs in small wave condition power generation technology, and the mini wave power generation devices for navigation lights have been commercialized. Some technologies have broken through the key technologies of long-term sea trial power generation, but most wave energy technologies are still solving technical difficulties in reliability, practicality, and efficient conversion. According to incomplete statistics, China has developed more than 40 wave energy devices with a capacity of 10 kilowatts to 1000 kilowatts, and most of the devices have completed sea trials. However, due to various reasons such as insufficient basic theoretical research, the operation effect of the devices in actual sea conditions is poor, and problems such as low power generation efficiency and easy damage to the devices occur during sea trials, indicating that the reliability and stability of China's wave energy power generation devices in actual sea conditions are urgently needed to be broken through.

This paper focuses on the research of key technologies for stable power generation of wave energy.

2. Basic Principles of Sea Waves

There are many reasons for the generation of waves on the sea surface, such as wind, changes in atmospheric pressure, celestial tidal forces, and submarine earthquakes. The so-called sea waves usually refer to wind waves generated by the action of wind on the sea surface. Wind waves are directly affected by wind force and are a kind of forced waves.The size of wind waves depends on the magnitude of wind speed, wind duration, and fetch. Due to the complex and changeable wind speed and direction, the waves caused by the wind are also extremely complex in form, with extremely irregular waveform and uncertain propagation directions. It is impossible to describe them with simple deterministic mathematical formulas, so wind waves are often referred to as irregular waves.The waves that still exist on the sea surface after the wind subsides or the wind waves that move out of the wind area are called swell. Swell belongs to free waves. Unlike wind waves, swell shows more regular wave crests and troughs, and the waveform is also smoother. The farther away from the wind area, the more regular the waveform. During the propagation of swell in deep water, some energy will be lost due to the friction inside the water body and the friction between the wave surface and the air. The main energy is consumed when it enters the shallow water area due to the bottom friction and turbulence when breaking. Waves play a very key role in the movement of sediment in coastal areas. Waves can not only stir up the sediment on the shore but also cause nearshore currents. Understanding the characteristics of wave motion is very important for studying the movement of nearshore sediment, the evolution of beaches, and their impact on wave energy devices.

Waves can be classified according to different classification criteria:

1) According to their shape, they can be divided into regular waves and irregular waves;
2) According to the water depth of the propagation sea area, they can be divided into deep-water waves and shallow-water waves;
3) According to their motion state, they can be divided into oscillatory waves, progressive waves, standing waves, and Stokes waves;
4) According to whether they break or not, they can be divided into breaking waves, unbroken waves, and post-breaking waves.

In addition, according to the kinematic and dynamic treatment methods of wave motion, waves can be divided into small-amplitude waves and finite-amplitude waves. Sometimes small-amplitude waves are also called linear waves, and finite-amplitude waves are also called nonlinear waves.

Wind waves have nonlinear three-dimensional motion characteristics and obvious randomness, and it is not easy to make an accurate mathematical description. However, for the relatively simple two-dimensional plane waves, the motion control equation of waves is illustrated by the simplest two-dimensional free oscillation progressive waves, as shown in Figure 1. The water depth h is taken as a constant, the x-axis is located on the still water surface, and the z-axis is vertically upward as positive. The waves move in the xz plane.

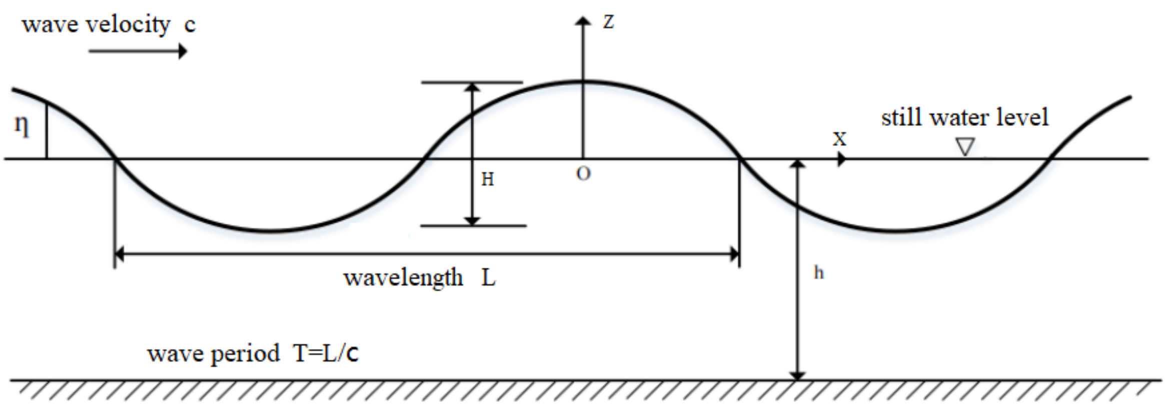


Figure 1 Definition of Basic Characteristic Parameters for Advancing Waves

Note:

Amplitude A: The vertical distance from the wave center to the wave crest;

Wave height H: The vertical distance from the bottom of the trough to the top of the crest, H=2A;

Wavelength L: The horizontal distance between two adjacent wave crests;

Wave period T: The time required for the wave to advance one wavelength;

Wave surface elevation η=η(x,t): The vertical displacement from the wave surface to the still water level.

The simplest form of a wave is a harmonic wave, and its wave surface can be represented by a cosine (or sine) function, that is:

$$\eta = A\cos(kx - \sigma t) \tag{1}$$

where: $kx - \sigma t$ is the phase function; k is the wave number, representing the number of waves in a length of 2π; $\sigma = \frac{2\pi}{T}$ is the circular frequency, the wave frequency is f=1/T, representing the number of wave oscillations per unit time.

The wave speed c is defined as the propagation speed of the wave shape, that is, the speed of the same phase point, also known as the phase speed. Figure 2 shows the wave surface curve at t=0 and $t=t_0$. When t=0, η=A, the wave crest point (η=A) is at x=0; when $t=t_0, \eta = A\cos(kx - \sigma t)$, the wave crest point (η=A) is at $x = \sigma t_0 / k$. Because the wave shape represented by the above formula propagates in the positive x direction, its wave shape propagation speed c is:

$$c = \frac{\sigma t_0 / k - 0}{t_0} = \frac{\sigma}{k} = \frac{L}{T} \qquad (2)$$

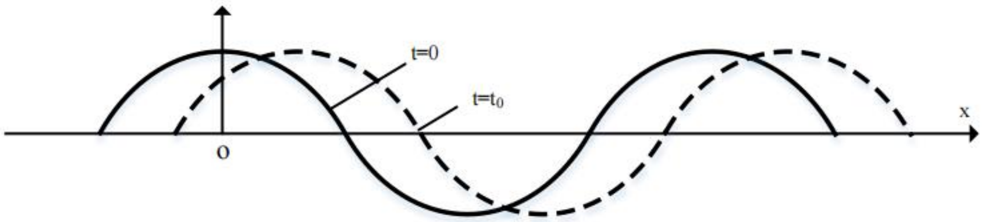


Figure 2 Wave Shape Propagation

Generally speaking, any specific wave train will be determined by the parameters H, L, and h or H, T, and h. Therefore, any wave theory is to determine its motion characteristics according to these three basic parameters, such as wave propagation speed, water particle motion speed, and trajectory.

When establishing a simple wave theory, the following assumptions are generally made to simplify: the fluid is homogeneous and incompressible, with a constant density; the fluid is an ideal fluid without viscosity; the pressure on the free water surface is uniform and constant; the water flow movement is irrotational; the seabed is horizontal and impermeable; The mass force is only gravity, and surface tension and Coriolis force can be neglected; the wave belongs to planar motion, that is, two-dimensional motion in the xz plane.

3. Wave Energy Generation Technology

Currently, the principles and deployment methods of wave energy conversion technology are not unified, with a wide variety of types and continuously emerging new technologies. Overall, wave energy utilization technologies are mostly derived from the following basic principles: converting wave energy into mechanical energy by utilizing the heaving and swaying movements of objects under the action of waves; converting wave energy into the potential energy of water by utilizing the climbing of waves, etc. The vast majority of wave energy conversion systems consist of three levels of energy conversion mechanisms. One level of energy conversion is the conversion of wave energy into mechanical energy for hydraulic cylinder movement by wave energy capture devices; Secondary energy conversion refers to the conversion of mechanical energy[11] from hydraulic cylinder motion into hydraulic energy; Third level energy conversion is the process of converting hydraulic energy into electrical energy through a hydraulic generator.

The energy conversion process of a hydraulic wave energy device is shown in Figure 3.

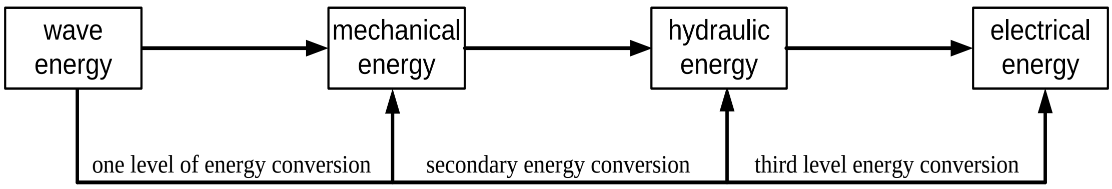


Figure 3 Energy Conversion Process Diagram of Hydraulic Wave Energy Device

The schematic diagram of the hydraulic wave energy conversion structure [12-14] is shown in Figure 4.Hydraulic oil is injected into the working chamber of the hydraulic cylinder through a one-way valve. The wave energy absorbing float moves reciprocally under the action of waves, driving the double-rod hydraulic rod, converting the unstable wave energy into hydraulic energy. The high-pressure hydraulic oil carrying unstable energy is pressed into the accumulator for storage through the hydraulic pipeline. As the hydraulic oil is continuously pressed into the accumulator, the internal pressure of the accumulator gradually increases. When the pressure at the inlet of the hydraulic motor reaches the set starting pressure, the hydraulic autonomous control valve automatically opens, and the high-pressure hydraulic oil drives the hydraulic motor, which in turn drives the generator set to generate electricity. As the hydraulic oil is gradually released, the internal pressure of the accumulator gradually decreases. When the pressure at the motor inlet is lower than the set stop pressure, the hydraulic autonomous control valve automatically closes, the generator set stops generating electricity, and the accumulator starts to store energy again [15-18]. The low-pressure hydraulic oil after work returns to the oil tank through the return oil pipeline, preparing for the next working cycle.

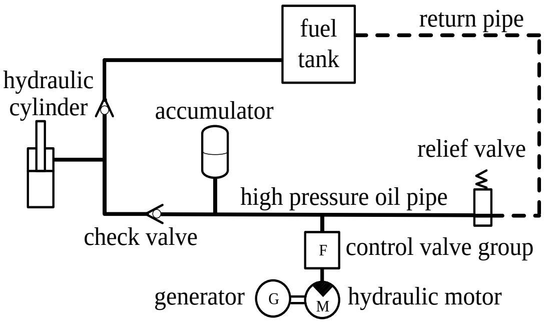
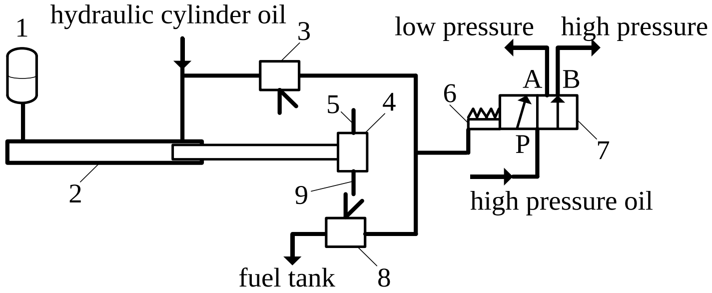


Figure 4 Schematic Diagram of Hydraulic Wave Energy Energy Conversion Structure

The working principle of the hydraulic autonomous control valve [19] is shown in Figure 5. In the initial state, the hydraulic rod of the control hydraulic cylinder is at the far right. The slider connected to the hydraulic rod and the two side levers are also at the far right. Ball valve b is in the open state, while ball valve a is closed. Therefore, no hydraulic oil enters the pilot block of the hydraulic directional control valve. The inlet P of the hydraulic directional control valve is connected to A and disconnected from B, and the hydraulic cylinder circuit is connected to the low-pressure oil circuit.

When the wave increases, the hydraulic oil pressure in the hydraulic cylinder slowly rises. The piston rod pulls the slider to move to the left. The lower lever on the slider will first push the handle of ball valve b until the handle of ball valve b rotates 45°. Ball valve b will then close, and P continues to be connected to A and disconnected from B. As the hydraulic oil pressure in the hydraulic cylinder continues to rise, the slider continues to move to the left until it pushes the handle of ball valve a to the left end, opening ball valve a. P is then connected to B and disconnected from A, and the hydraulic cylinder circuit is connected to the high-pressure oil circuit. The hydraulic system begins to do work.

When the wave decreases, the pressure in the hydraulic cylinder also gradually decreases. The slider moves to the right, and the handle of ball valve a rotates to the right until ball valve a closes. At this time, ball valve b is also in the closed state, with P connected to B. As the slider continues to move to the right, ball valve b opens, the hydraulic oil in the pilot block circuit is released, the circuit pressure is unloaded, and the hydraulic directional control valve reconnects P to A under the action of the spring, stopping the work. The hydraulic autonomous control valve returns to its initial state.

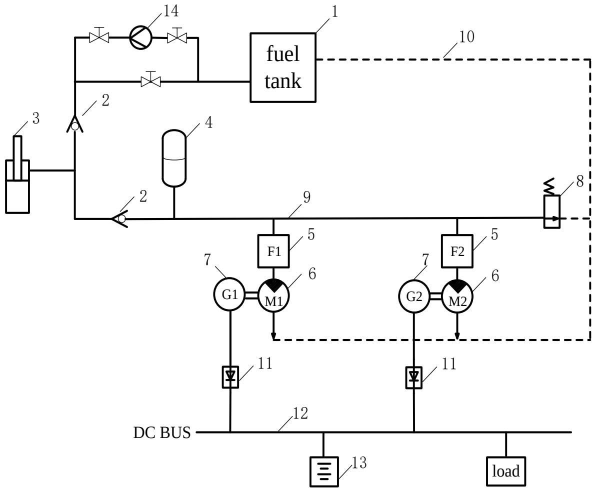


1.auxiliary accumulator 2.control hydraulic cylinder 3.ball valve a 4.slider 5.upward shift lever 6.lead block 7.Hydraulic directional valve 8. ball valve b 9.pull down lever

Figure 5 Schematic Diagram of Hydraulic Autonomous Control Valve Principle

4. Wave Energy Generation Step-Pressure Control Technology

For the convenience of analyzing and optimizing problem-solving, a wave energy generation system equipped with two generators is taken as an example. Wave energy generation devices with a capacity of tens of kilowatts or more generally have at least two generator sets, as shown in Figure 6.



1.oil tank 2.check valve 3.hydraulic cylinder 4.accumulator 5.control valve 6.hydraulic motor 7.generator 8.relief valve 9.high-pressure oil pipe 10.return oil pipe 11. AC/DC rectifier 12.DC bus 13.lithium battery 14.test oil pump

Figure 6 Schematic Diagram of Two-Generator System

The control strategy of the hydraulic autonomous control valve for power generation generally has two characteristics: step-pressure setting and high-low power matching of generators, as shown in Table 1. The control valve action is realized using a mechanical pressure switch, and the start-stop pressure switch of the generator is set in steps.

Table 1 Step-Pressure Setting

Generator	Start Pressure (MPa)	Stop Pressure (MPa)	Rated Power (kW)
G1	16	10	10
G2	17	11	20

The total power generation and hydraulic system waveform [7] are shown in Figure 7.

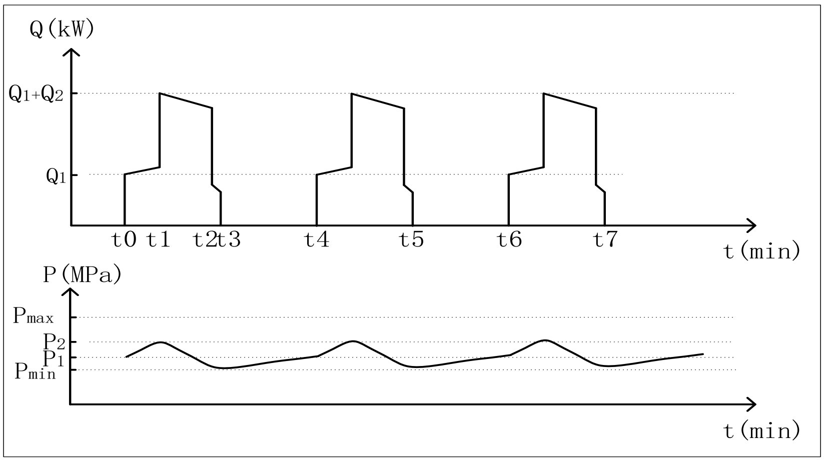


Figure 7 Total Power Generation and Hydraulic System Waveform Diagram

From Figure 7, it can be seen that although hydraulic energy overcomes the When waves come, the wave-absorbing float moves up and down, driving the hydraulic cylinder 3 to compress the turbine oil into the accumulator 4, compressing the air bag inside the accumulator 4. When the oil pressure in the high-pressure oil pipe 9 reaches the start pressure P_1 of the hydraulic motor M1 (t0), the control valve group F1 is conductive, the hydraulic motor M1 starts, and drives the generator G1 to generate electricity, with a power generation power of Q_1. When the oil pressure in the high-pressure oil pipe 9 reaches the start pressure P_2 of the hydraulic motor M2 (t1), the control valve group F2 is conductive, the hydraulic motor M2 starts, and drives the generator G2 to generate electricity, with a total power generation power of Q_1+Q_2. When the oil pressure is less than P_2-ΔP_2 (hysteresis value), the hydraulic motor M2 stops; when the oil pressure is less than Pmin, the hydraulic motor M1 stops.
randomness of wave energy, under the control method of the hydraulic autonomous control valve, a wide-pulse power generation waveform is formed, resulting in discontinuous total power generation. During the interruption period of power generation, an external power source is required to provide power for the electrical equipment of the wave energy generation device.

5. Stable Control Optimization of Wave Energy Generation

5.1 Optimization Technology Route

To enable the wave energy generation system to buffer the impact of large waves, the high-pressure accumulator in the hydraulic system generally stores energy sufficient for the smallest displacement hydraulic motor to operate continuously for about 5 minutes.
The power of the hydraulic motor generator [20] is given by:

$$P_G = q \times \Delta p \times n \times \eta_{mh} \times \eta_G / 60000 \quad (3)$$

where $P_G$is the rated power of the generator (kW), q is the displacement of the motor (ml/r), Δp is the pressure difference between the motor's inlet and outlet (MPa), n is the rated speed of the motor (r/min), η_{mh} is the efficiency of the hydraulic motor, and η_G is the efficiency of the generator.

The pressure difference Δp between the motor's inlet and outlet is equal to the difference between the hydraulic system pressure and the return oil pipe pressure. Since the return oil pipe is connected to the oil tank under atmospheric pressure, its pressure can be neglected compared to the hydraulic system pressure, so Δp can be directly taken as the hydraulic system pressure.
Equation (3) can be transformed into:

$$P_G = q \times p_{acc} \times n \times \eta_{mh} \times \eta_G / 60000 \quad (4)$$

where $P_{acc}$is the accumulator pressure (i.e., the hydraulic system pressure) (MPa).
The fundamental reason for the wide-pulse power generation waveform formed by the hydraulic autonomous control valve is the unreasonable start-stop time of G2, which does not adjust in real-time according to the current wave energy size, and excessive power generation by G1 reduces the power generation time of G2. The optimization control technology route for power generation is to dynamically control the start-stop time of the G2 generator based on real-time prediction of wave energy size, to maintain the longest power generation time of G1, and replace the hydraulic autonomous control valve with an electromagnetic valve to achieve dynamic start-stop of the hydraulic motor.

5.2 Real-time Prediction of Wave Energy

Control the test oil pump to perform pressurization operations and test the amount of electricity that the accumulator can generate when releasing from any initial pressure to the minimum working pressure, and establish the following power generation function:

$$W(P) = \int_{P_{min}}^{P} Q(t)\,dt, P_{min} \le P \le P_{max} \tag{5}$$

where W(P) is the amount of power generation (kWh), Q(t) is the total power generation at time t, $P_{min}$is the minimum working pressure, and $P_{max}$is the maximum working pressure.

According to the power generation function mentioned above, calculate the maximum time that the accumulator can maintain the factory power supply:

$$T_x = W(P_{max})/Q_{min} \tag{6}$$

where $T_x$represents the maximum time that the accumulator can maintain the factory power supply, and $Q_{min}$is the minimum generator power.

Real-time calculation of the average power Q_{ave}within the recent 3Txperiod as the predicted value of wave energy generation power:

$$Q_{ave} = \frac{1}{3T_x}\left[(W(P_{3Tx}) - W(P_0) + \int_0^{3T_x} Q(t)dt \right] \tag{7}$$

where $W(P_{3Tx})$ is the amount of electricity that the accumulator can generate at pressure P_{3Tx}at 3Txmoment, $W(P_0)$ is the amount of electricity that the accumulator can generate at real-time calculation at 0 moment, and Q(t) is the real-time power generation.

5.3 Dynamic Calculation of Generator Start-stop Pressure

Dynamically calculate the set value of generator start-stop pressure and operating time:

$$\begin{cases} P'_{max} = P_{max} \\ P'_{min} = P_{min} \\ P'_1 = P'_{min} + \min\left[\max\left(L_{P1}, \frac{L_{P1} + K_1(H_{P1} - L_{P1})Q_1}{Q_{ave}} \right), H_{P1} \right] \\ P'_2 = P'_{max} - \min\left[\max\left(L_{P2}, \frac{L_{P1} + K_2(H_{P2} - L_{P2})Q_{ave}}{Q_{ave}} \right), H_{P2} \right] \\ t'_2 = \max\left(m, \frac{T_x Q_{ave} - T_x Q_1}{Q_2} \right) \end{cases} \tag{8}$$

where P'_{max} is the maximum working pressure used in the solenoid valve mode, $P'_{min}$is the minimum working pressure used in the solenoid valve working mode. The generator with smaller power generation in the device is taken as the first generator, and the generator with larger power generation in the device is taken as the second generator. $P'_1$is the start pressure of the first generator, $P'_2$is the start pressure of the second generator,$t'_2$is the operating duration of the second generator, $L_{P1}$is the lower limit value of the start pressure correction amount of the first generator, $L_{P2}$is the lower limit value of the start pressure correction amount of the second generator, $H_{P1}$is the upper limit value of the start pressure correction amount of the first generator, $H_{P2}$is the upper limit value of the start pressure correction amount of the second generator, $K_1$is the start pressure coefficient of the first generator, $K_2$is the start pressure coefficient of the second generator, Q_1 is the power generation power of the first generator, $Q_2$is the power generation power of the second generator, $Q_{ave}$is the average power generation power, $T_x$is the maximum time that the accumulator can maintain the factory power supply, and m is the lower limit value of the operating duration of the second generator.

6. Simulation Verification

6.1 Simulation Model

Based on the basic working principle of the hydraulic energy storage power generation system, a hydraulic energy storage power generation system model with two power generation branches was built using MATLAB Simulink software, as shown in Figure 8. The system mainly consists of a hydraulic energy storage part, a hydraulic power generation part, and a converter part. The key equipment includes an accumulator unit, two hydraulic power generation units, two rectifier units, and a DC voltage load unit. The main parameters of the simulation model are shown in Table 2.

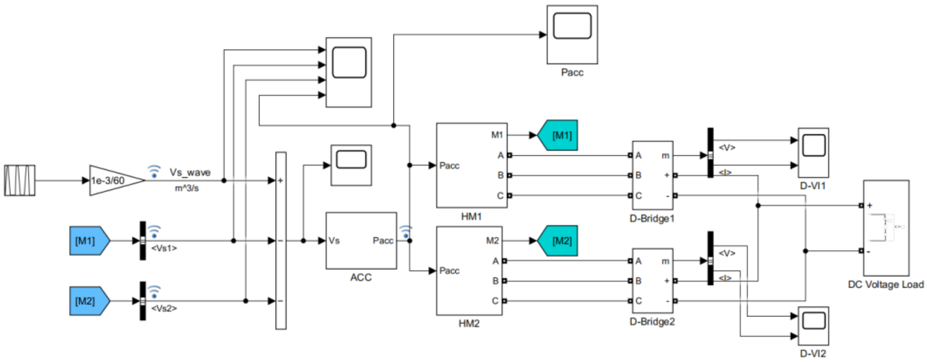


Figure 8 Simulation Model of Hydraulic Wave Energy Power Generation System

Table 2 Main Parameters of Simulation Model

Name	Value	Unit
Accumulator Capacity	60.0	L
Accumulator Precharge Pressure	40.0	Bar(0.1MPa)
Hydraulic Motor Displacement	125.0	cm^3/rev
Hydraulic Motor Unit Torque	1.99	N·m/bar

6.2 Simulation Experiments

1) Test Condition 1: When the amplitude of the wave energy simulation signal source is 1500mm and the period is 6min, the power generation waveform under the hydraulic autonomous valve control(HAVC) mode is shown in Figure 9, It reveals the relationship between the flow of high-pressure hydraulic oil generated by a wave-driven hydraulic cylinder, the flow consumed by two hydraulic motors, and the pressure variations in the accumulator. The waveform of the total power generation is shown in Figure 10, where 'Total Power' represents the total power generation, and 'Qave' denotes the average power.

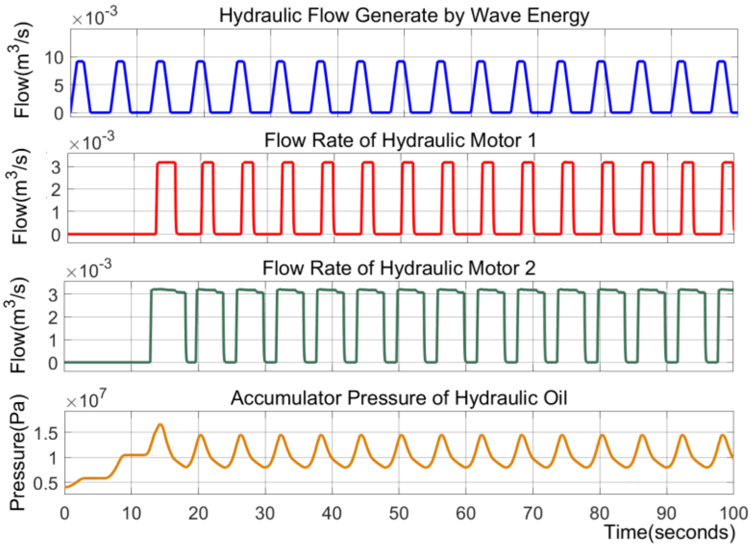


Figure 9 Condition 1: Power Generation Waveform under HAVC Mode

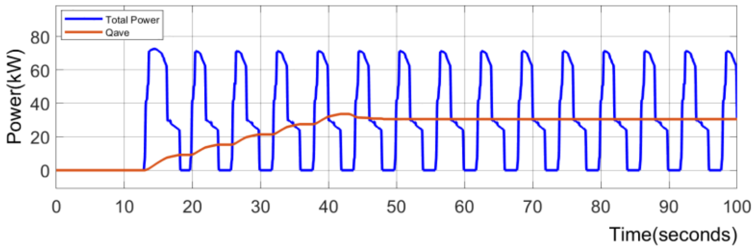


Figure 10 Condition 1: Total Power Generation Waveform under HAVC Mode

The power generation waveform after optimization control is shown in Figure 11,the total power generation waveform is shown in Figure 12.

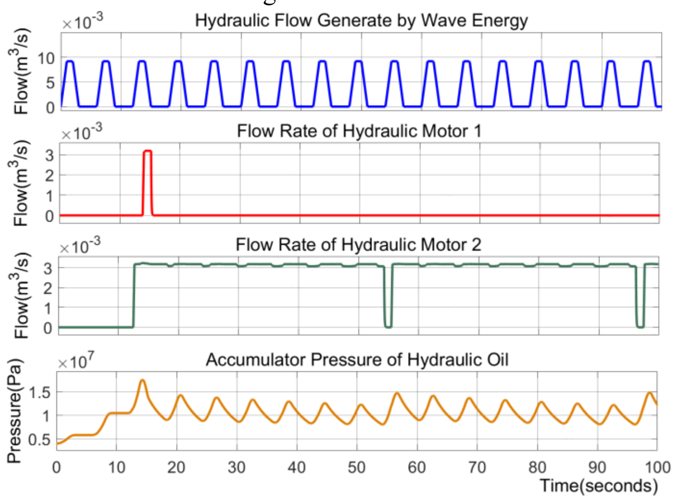


Figure 11 Condition 1: Power Generation Waveform after Optimization Control

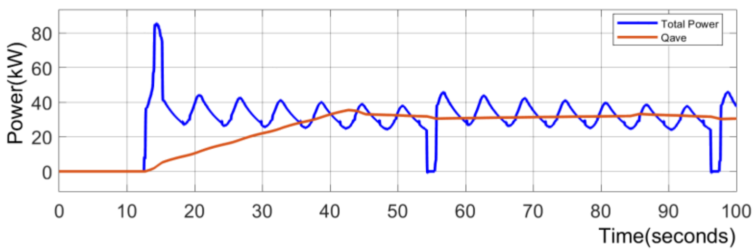


Figure 12 Condition 1: Total Power Generation Waveform after Optimization Control

Comparing the waveform in Figure 9 and Figure 11, it can be seen that under the HAVC mode, the two generators stopped periodically at the same time 14 times, and the accumulator pressure control range was 8.1~16.6MPa. After optimization control, the two generators only stopped at the same time twice, basically maintaining the operation of the G2 generator, and the accumulator pressure control range was 9.0~17.5MPa. Comparing the waveform in Figure 10 and Figure 12, it can be seen that after optimization control, the fluctuation amplitude of the total power generation waveform decreased.

2) Test Condition 2: When the amplitude of the wave energy simulation signal source is 2000mm and the period is 6min, the power generation waveform under the HAVC mode is shown in Figure 13, the total power generation waveform is shown in Figure 14.

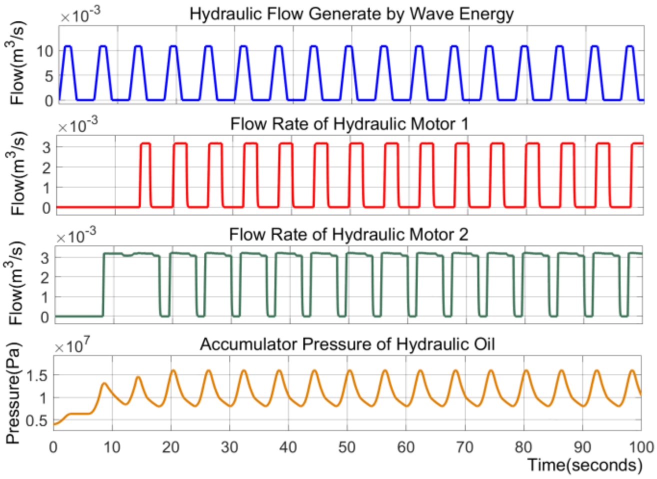


Figure 13 Condition 2: Power Generation Waveform under HAVC Mode

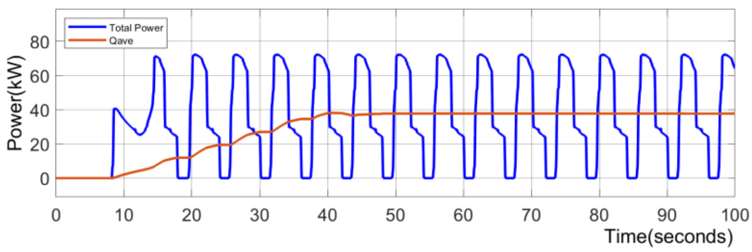


Figure 14 Condition 2: Total Power Generation Waveform under HAVC Mode

The power generation waveform after optimization control is shown in Figure 15,the total power generation waveform is shown in Figure 16.

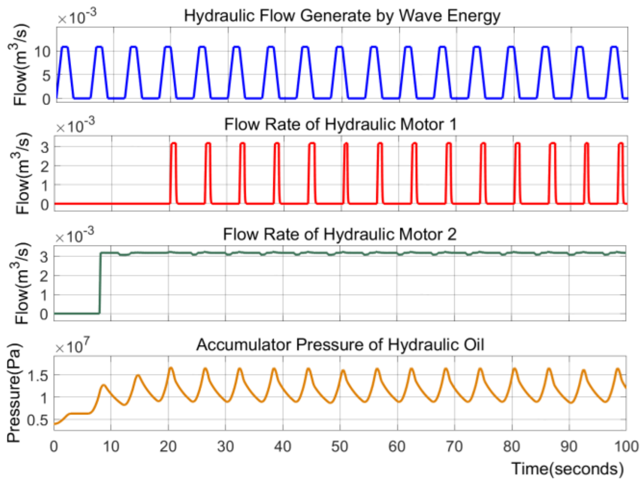


Figure 15 Condition 2: Power Generation Waveform after Optimization Control

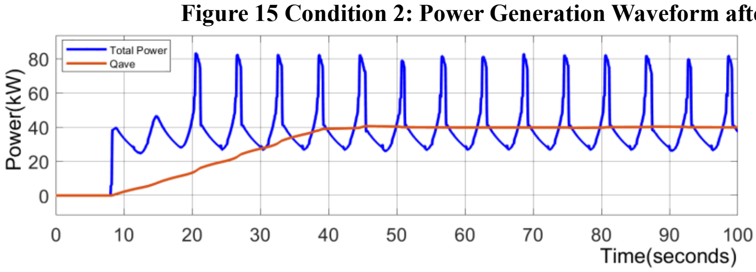


Figure 16 Condition 2: Total Power Generation Waveform after Optimization Control

Comparing the waveform in Figure 13 and Figure 15, it can be seen that under the HAVC mode, the two generators stopped periodically at the same time 14 times, and the accumulator pressure control range was 8.0~16.0MPa. After optimization control, there was no situation where the two generators stopped generating power at the same time, and the G2 generator was always maintained in operation, with the accumulator pressure control range being 8.9~17.9MPa. Comparing the waveform in Figure 14 and Figure 16, it can be seen that after optimization control, the fluctuation amplitude of the total power generation waveform decreased.

7. Conclusions

This paper investigates the issue of discontinuous total power generation in hydraulic wave energy generation systems controlled by hydraulic autonomous control valves and proposes a control strategy for stable total power generation. The specific conclusions are as follows:

1) The root cause of discontinuous total power generation was revealed: Under the control method of hydraulic autonomous control valves, the start and stop times of the generator are not adjusted in real-time according to the magnitude of the current wave energy, which fails to fully utilize the ‘valley-filling’function of hydraulic energy storage.

2) A real-time wave energy prediction method applicable for control optimization was proposed: This includes the establishment of a hydraulic-power generation function and the calculation method for predicting wave energy. These methods enable more accurate prediction of wave energy, providing a more rational basis for the start and stop of the generator.

3) A calculation method for dynamic generator start/stop pressure settings and operating time was proposed: By dynamically adjusting the start/stop pressure and operating time of the generator, the 'valley-filling' function of hydraulic energy storage is fully utilized to optimize the power generation process.

4) Through modeling and simulation experiments, the interruption of total wave energy power generation was significantly reduced under multiple operating conditions: This improvement enhances the quality and reliability of wave energy power generation and creates favorable conditions for subsequent power filtering and rectification.

References

1. W Li, HD Shi, Z Liu, *et al*. The Current Status of Marine Energy Research in China and Suggestions for Future Development. Solar Energy. 2024; (7):79-88. DOI:10.19911/j.1003-0417.tyn20240603.01.

2. XN Wang, CL Ma. Exploitation and Utilization of Marine Renewable Energy Resources Under the Dual Carbon Goals. Huadian Technology. 2021; 43(11):91-96. DOI:10.3969/j.issn.1674-1951.2021.11.011.

3. FM Jing, XR Wang, YL Mei. Current Development Status and Key Technical Challenges of Marine Energy Utilization Technologies. Ship Engineering. 2025; 47(1): 4-20. DOI:10.13788/j.cnki.cbgc.2025.01.Z1.

4. OES Annual Report 2019. The Executive Committee of Ocean Energy Systems, https://www.ocean-energy-systems.org/publications/oes-annual-reports/.

5. YB Chen, J Huang, SR Lai, *et al*. Current Situation and Key Technologies of Wave Power Generation. Hydropower and New Energy. 2020; 34(1):33-35+43. DOI:10.13622/j.cnki.cn42-1800/tv.1671-3354.2020.01.009.

6. KJ Feng, GT Ning, LY Huang, *et al*. Research on the Development and Utilization of Wave Energy in the South China Sea Islands. Metallurgical Collections. 2020; 5(20):216-217. DOI:10.19537/j.cnki.2096-2789.2020.20.101.

7. YQ Zhang. 100kW-Model Experimental Study on a Multi-body Floating Eagle-type Wave Energy Power Generation Device. Journal of Ocean Technology. 2014; 33(4):73-80.

8. KL Wang, SW Sheng, YG You, *et al*. Research on Redundant Monitoring Technology for the 'Eagle One' Floating Wave Energy Device. Journal of Ocean Technology. 2014; 33(4):62-67.

9. SW Sheng, YQ Zhang, KL Wang, *et al*. Research on the 'Eagle One' Wave Energy Power Generation Device. Ship Engineering. 2015; 37(9):104-108. DOI:CNKI:SUN:CANB.0.2015-09-026.

10. SW Sheng, KL Wang, HJ Lin, *et al*. OPEN SEA TESTS OF 100 kW WAVE ENERGY CONVERTOR SHARP EAGLE WANSHAN. Acta Energiae Solaris Sinica. 2019; 40(3):709-714. DOI:CNKI:SUN:TYLX.0.2019-03-016.

11. Nie R, Scruggs J, Chertok A, *et al*. Optimal causal control of wave energy converters in stochastic waves Accommodating nonlinear dynamic and loss models. International Journal of Marine Energy. 2016; 15:41-55. DOI:10.1016/j.ijome.2016.04.004.

12. Y Ye, YG You, ZP Wang, *et al*. Research on the Hydraulic Automatic Stepwise Control System for Wave Energy Devices. Acta Energiae Solaris Sinica. 2019; 40(6):1481-1486. DOI:CNKI:SUN:TYLX.0.2019-06-001.

13. YQ Zhang, SW Sheng, YG You, *et al*. Design on Hydraulic Energy Storage System of Wave Energy Converters. Machine Tool & Hydraulics. 2016; (5):117-121. DOI:10.3969/j.issn.1001-3881.2016.05.030.

14. CH Liu,JK Fei,ZX Zhao, *et al*.Simulation Study on the Characteristics of a Wave Energy Conversion Hydraulic Power Take-Off System Based on Volume Regulation and Accumulator Pressure Stabilization. Journal of Mechanical Engineering. 2024; 60(20):327-338. DOI:10.3901/JME.2024.20.327.

15. ZP Wang, YG You, SW Sheng, *et al*. Experimental Study on the Hydraulic Autonomous Control System for Wave Energy Generation Devices under Real-Sea Conditions. Acta Energiae Solaris Sinic. 2019; 40(7):2085-2090. DOI:10.3969/j.issn.0254-0096.2014.10.040.

16. KL Wang, LF Tian, XH Wang, *et al*. Characteristics of the Power Generation System of Hydraulic Energy-Storage Wave Energy Devices. Journal of South China University of Technology: Natural Science Edition. 2014; 42(6):25-30. DOI:10.3969/j.issn.1000-565X.2014.06.005.

17. YQ Zhang, LF Yu, SW Sheng, *et al*. Research on the Hydraulic Energy Conversion System of Wave Energy Devices. Acta Energiae Solaris Sinic. 2014; 35(10):2071-2076. DOI:10.3969/j.issn.0254-0096.2014.10.040.

18. J Hua, DT Li, LX Chen, *et al*. Research on Hydraulic Transmission Systems Based on Accumulators. Ocean Development and Management. 2019; 36(12):80-84. DOI:10.3969/j.issn.1005-9857.2019.12.015.

19. JQ Jiang, YG You, SW Sheng, *et al*. Design and Experimental Study of a Hydraulic Autonomous Controller for a Wave Energy Device. Acta Energiae Solaris Sinic. 2014; 35(4):594-598. DOI:CNKI:SUN:TYLX.0.2014-04-007.

20. Hong GAO, Rui-zhi LIANG, Tetsuhiro TSUKIJI, *et al*. Investigation on Dynamic Characteristics and Wave Energy Conversion of Hydraulic System. Chinese Hydraulics & Pneumatics. 2019; (6) :1-4. DOI:10.11832/j.issn.1000-4858. 2019.06.001.