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Study of Power Decoupling Properties of Hydraulic Power Take-off System in Ocean Wave Converter

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Abstract. As a kind of ocean energy, wave energy is a renewable energy with the character of widespread, abundant and highly energy flux density. But the extracting energy from waves is limited for its unstable power input and characterized with input-output power coupling. To solve the problem a hydraulic transmission scheme for the power take off system is proposed and the hydraulic transformer principle is applied in the hydraulic circuit to achieve variable pressure network to constant pressure network and power input-output decoupling. Accumulator is installed in the circuit to absorb system pressure and flow pulsation. As a result, a constant power and speed output is achieved under different sea state condition. The mathematical model of the hydraulic power take off system is established and the simulation results show that it is possible to obtain a constant frequency and smooth voltage output from an ocean wave converter.

Keywords: ocean wave conversion, power decoupling, hydraulic power take off system.

1. Introduction

Ocean wave energy is an inexhaustible renewable energy which exists in ocean as a form of mechanical energy. Ocean wave energy offers the highest energy density among renewable energy sources such as tidal energy, wind energy, solar energy, ocean thermal energy, osmotic power [1]. Wave energy converter (WEC) is a kind of device through which trapped wave can be converted to a particular form of mechanical or hydraulic energy. A significant challenge in the ocean wave energy conversion is the conversion of the slow, random, and high-force oscillatory motion into useful motion to drive a generator with output quality acceptable to the utility network. As waves vary in height and period, their respective power levels vary accordingly [2]. As a result, WEC device requires a power take off (PTO) system to achieve speed alteration, power transmission and control. According to the current study, three kinds of PTO system always be taken into consideration: gearbox, direct drive and hydraulic. The transmission ratio of gearbox is limited and cannot smooth the impact of wave, so the lifetime of generator is short. Considering the current low-speed permanent magnet synchronous generator technology is not mature enough and the harsh marine environment, the cost of direct-drive transmission is much higher. Another method of converting the low-speed oscillating motion of the primary WEC interface is to employ a hydraulic system which is characterized as high power density, compact structure, highly response and easy to perform overload protection. Hydraulic transmission is becoming a first choice in WEC [3].

At present, the research of hydraulic PTO system is focused on the application of advanced control strategies to improve energy efficiency and the reliability. The large capacity accumulator is commonly used in the hydraulic PTO system to smooth the flow and pressure fluctuation. Ronan Costello et.al [4] analyzed both the variable pressure systems and constant pressure systems in the efficiency and speed regulation characteristics. The mathematical modes of these two systems are established to give explanation. G. S. Payne and A. E. Kiprakis et.al [5] proposed a new digital hydraulic pump/motor specialized in the

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application of hydraulic PTO system in WEC with high volumetric and mechanical efficiency. J. A. M. Cretel and G. Lightbody et.al [6] perform a comprehensive compare among several nonlinear control method and put forward the idea of using optimal control strategy. Ross Henderson [7] discusses the principle and displays the experiment data of Pelamis wave power device developed by the British OPT company. Only high capacity accumulator is applied in Pelamis to achieve input and output power decoupling and energy storage. It shows high reliability of the hydraulic PTO system and the successful of Pelamis lay a good foundation of hydraulic application in ocean wave energy harvesting.

In this paper, a novel hydraulic PTO system is proposed to achieve input and output power decoupling. The principle of hydraulic transformer is applied which is characterized by using two separate hydraulic circuits and motor shaft drive a variable displacement pump that converts the mechanical power again into hydraulic power at an arbitrary high pressure level. At the same time accumulator is used to buffer the pressure and flow fluctuation. As a result, it is possible to obtain a constant frequency and smooth voltage output from an ocean wave converter.

2. The Hydraulic PTO System

2.1. System Composition

As shown in Fig.1, the system author proposed is divided into energy capture unit, rectifier, pressure regulator, energy storage unit and driver. The unstable variable power input can be converted to stable power output which can drive generator working at constant speed, that is, from variable pressure circuit to constant pressure circuit. This hydraulic PTO system is different from the previous for its using two independent circuits to achieve the decoupling of the input and output power.

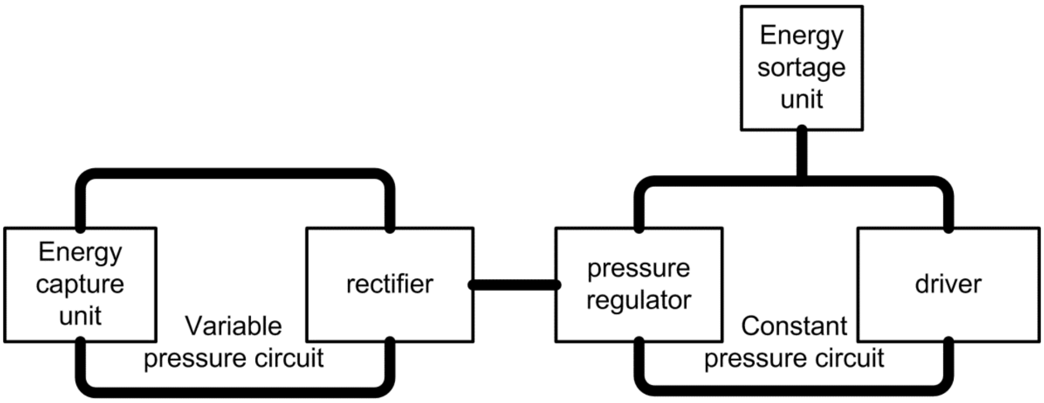

Fig. 1: Composition of the WEC hydraulic power PTO system

2.2. Working Principle Analysis

Fig. 2 is the hydraulic schematic of PTO system proposed. Energy capture device (buoy) oscillates by the driving of ocean wave. The rod of the hydraulic cylinder cy_1 is forced up and down which forced fluid through four check valves $C_1 - C_4$, rectifying the flow, to a hydraulic motor M_1. Variable displacement pump M_p is driven by motor M_1 pumping high pressure oil to drive hydraulic motor M_2 and generator G is driven by M_2 to generate voltage electricity. The circuit pressure is set by relief valve r_1, r_2 and r_3. Accumulator Acc_1 is used to buffer pressure and flow fluctuation. A velocity measurement circuit is consists of cylinder cy_2, pump p_1 and throttle valve k_1. This is the key factor to achieve the input-output power decoupling.

The hydraulic circuit of Fig.2 has been analyzed under the following assumptions:

(1) The volumetric and mechanical losses of motor, pump, cylinders and accumulator are neglected.
(2) Regarding the linking of motor and variable pump is stiffness enough.
(3) The dynamics of the swash plate mechanism of the hydraulic motors has been neglected.
(4) The fluid compressibility is neglected.
(5) The pressure of oil back to the tank is regarded as zero.

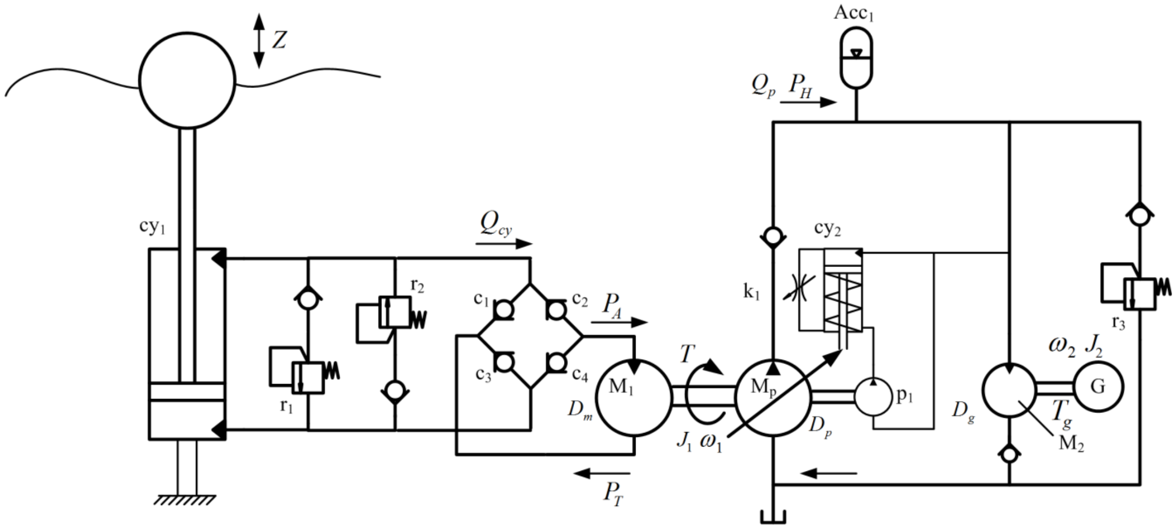

Fig. 2: Schematic diagram of hydraulic PTO system with input-output power decoupling in WEC

For variable pump M_p, the volumetric flow of pump M_p is:

$$Q_p = \omega_1 D_p - c_{tp} P_H \tag{1}$$

Where Q_p is the volumetric flow through variable pump M_p, ω_1 is the pump shaft speed and c_{tp} is the leakage coefficient of pump M_p. P_H is the outlet pressure of pump M_p.

For the hydraulic circuit be composed by pump M_p and motor M_2, according the equation of continuity, Eq.2 can be developed as:

$$Q_p = D_g \omega_2 + c_{tm2} P_H \tag{2}$$

Where ω_2 is the speed of motor M_2 and D_g is the radian displacement of motor M_2, c_{tm2} is the leakage coefficient of M_2.

According the equation of moment equilibrium, Eq.3 can be developed:

$$P_H D_g = T_g + B_2 \omega_2 + J_2 \dot{\omega}_2 \tag{3}$$

Where T_g is the load torque generated by generator G, J_2 is the total moment of inertia of components loaded on the shaft of motor M_2. B_2 is the viscous damping coefficient of motor M_2 shaft and ω_2 is the speed of generator. Substituting Eq.3 to Eq.1 and Eq.2 and take the Laplace Transform, the relation between output speed of motor M_2 and input speed of pump M_p is

$$\omega_1 D_p D_g - \left(c_{tm2} + c_{tp}\right) T_g = D^2{}_g \omega_2 + \left(c_{tm2} + c_{tp}\right)\left(B_2 + J_2 s\right)\omega_2 \tag{4}$$

Considering $c_t = c_{tm2} + c_{tp}$ is the total leakage coefficient of hydraulic circuit

$$\omega_2 = \frac{D_p D_g}{D^2{}_g + c_t\left(B_2 + J_2 s\right)}\omega_1 - \frac{c_t T_g}{D^2{}_g + c_t\left(B_2 + J_2 s\right)} \tag{5}$$

The flow rate of cylinder cy_1 is

$$Q_{cy} = D_m \omega_1 + c_{tm1} P_A \tag{6}$$

Where c_{tm1} is the leakage coefficient of motor M_1 and D_m is the displacement of M_1, ω_1 is the speed of M_1, P_A is the static pressure of circuit.

Some conclusion can be drawn from Eq.1 to Eq.6. As the flow rate Q_{cy} increase, part of it can be absorbed by accumulator Acc_1 and the rest of it causes the increasing speed of pump M_p, that is ω_1. This is equivalent to increasing the flow rate of the pump and will inevitably lead to an increase in generator speed as the load torque is constant. If the displacement of variable pump M_p is decreased the effect of ω_1 to ω_2 can be neutralized and the speed of motor M_2 is stabilized. The swash plate mechanism adjustment is achieved by pump P_1 and cylinder cy_2. Pump P_1 provide a controllable flow rate proportional to the speed. This will cause a pressure difference across the throttle valve k_1. The swash plate angle will be changed by cylinder cy_2 under the shifting pressure. The alteration of volumetric displacement of M_p caused the corresponding changing of output torque and output speed. This process will not stop until the pressure equilibrium of cylinder cy_2 constructed. The continuously speed change can be achieved by changing the throttle valve port area of k_1.

In general, this method of de-coupling is achieved by converting the hydraulic input power at a fixed displacement motor into mechanical rotary power. The motor shaft drives a variable displacement pump that converts the mechanical power again into hydraulic power at an arbitrary high pressure level. This method transform the wave dependent variable input pressures and flow rates into different output pressures and flow rates at constant theoretical power throughput. The power generation is completely decoupled from the input by using two separate hydraulic circuits.

3. Simulation

In order to verify the decoupling functionality of the hydraulic PTO concept, Simulation of system steady state characteristics, fluctuation characteristics and conversion efficiency is performed based on Matlab 7.0 and AMESim Rev10. Matlab is used here to establish a hydrodynamic model and AMESim is applied to setup a hydraulic system model. On the basis of co-simulation the effectiveness of PTO system design is verified.

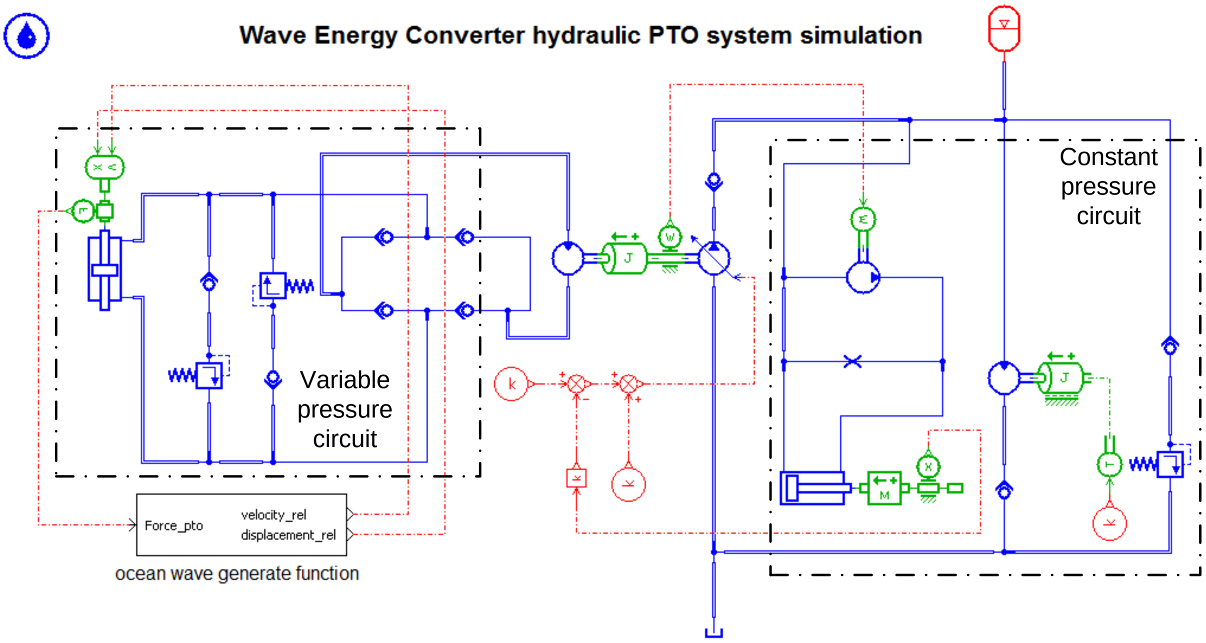

Fig. 3: Simulation model of power take off system in wave energy converter

Fig.3 shows the simulation model of hydraulic PTO system discussed. The hydrodynamic model is based on the K-F theory discussed in [8] and can in brief be discribed by the Eq.7 and Eq.8.

$$Z = \frac{F_V}{\sqrt{\left[\rho g S_r + K_f - \omega^2 (m + m_w)\right]^2 + (\omega C_f)^2}} \tag{7}$$

$$K_f = F_{cy} / Z ? \quad C_f = -F_{cy} \quad \dot{Z} \tag{8}$$

Where Z is the heave displacement, F_V is the excitation forces act on the float. These two parameters can be calculated based on K-F theory according [9]. ρ is the density of sea water and g is the acceleration of gravity. S_r is the water plane area, ω the radian frequency of wave and $(m + m_w)$ is the cross terms of the added mass at infinite frequency. K_f and C_f are stiffness coefficient and viscous drag coefficients respectively. The output force F_{cy} by cylinder can be calculated from Eq.8. The wave data is generated according wave superposition method of linear wave theory [10]. In the paper amplitude 2m, wave pattern coefficient 0.8 and wave frequency 10 are selected. Hydraulic cylinder output force on the float of the initial state is taken into the Eq.7 and Eq.8 to calculate the heave displacement of float. The hydraulic cylinder speed is given by derivative of the displacement of cylinder and the output force of cylinder can be calculated by taking the speed into model aforementioned. The simulation process will complete through iteration. Table 1 list the parameters of simulation model.

Table 1: Simulation parameters of hydraulic power take off system in wave energy converter

Variable	Data	Units
Q_{cy}	1200	[L/min]
D_m	2000	[ml/rev]
D_p	400	[ml/rev]
D_g	100	[ml/rev]
D_{p1}	20	[ml/rev]
J_2	50	[Kg/m^2]
P_{ref}	100	[bar]
P_{rev}	50	[bar]
V_{acc}	40	[L]

4. Simulation Results

The float is excited by the wave profile generated by Eq.7 and Eq.8. It reacts with a relative motion displacement as depicted in Fig. 4. Fig. 5 shows the relative velocity responds curve. The instantaneous power and the average power can be calculated according to the output flow rate and pressure of hydraulic cylinder. Also the total input power into the system can be calculated by multiplying output force of transmission system and the velocity of energy capture device. In this paper the first is used and the instantaneous power to the system is shows in curve 1 of Fig. 6. The average power absorbed from sea wave and transmitted to the system is shows in curve 2 of Fig.6.

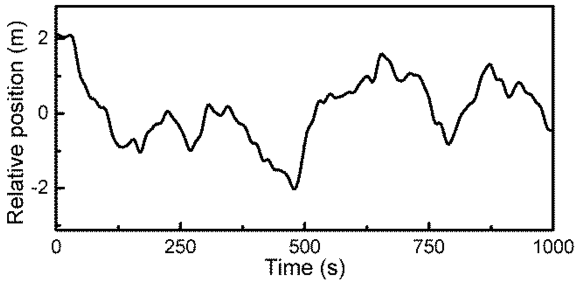

Fig. 4: Position curve of wave energy converter

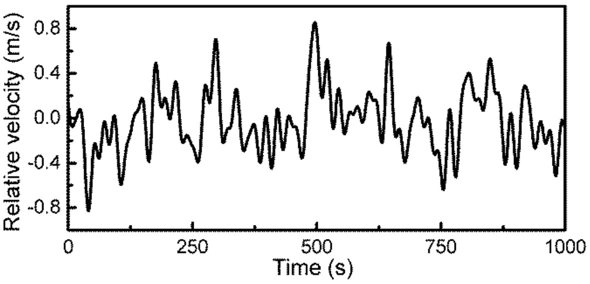

Fig. 5: Velocity curve of wave energy converter

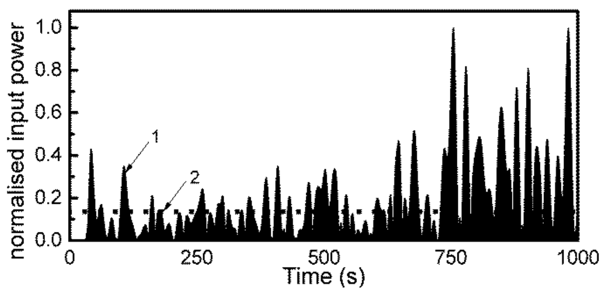

Fig. 6: Normalized input power to the PTO system

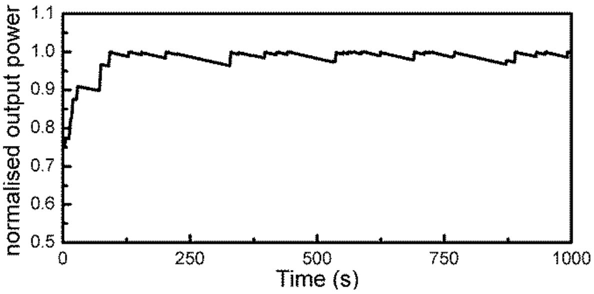

Fig. 7: Normalized output power of motor M_2

These data prove that there is a large power fluctuation input to the hydraulic PTO system and the ratio of mean to peak power is about 13.5%. Totally 80% of the time the input power to the PTO system is below the average power. However, the efficiencies of the hydraulic motors and the generator have not yet been included in the simulation model, so that the actual output power can be expected to be somewhat lower. This condition will take grate trouble to the design of PTO system. If the system is designed according to the average power the safety and reliability cannot be promised as the system working under peak power input.

If the hydraulic component is chosen according to the peak power the effectiveness will be much lower. This means that power peaks can be harvested fairly well, but for average power input, the units are considerably oversized. It also indicates that the power decoupling is a necessity for the PTO system.

Fig. 7 shows the normalized output power curve of motor M_2 through power decoupling by hydraulic transformer. It clearly proves the excellent smoothing performance of the hydraulic PTO circuit. The peak power is only 1.01 times of the average power and 95% of the time system output is about the average power. Fig.8 shows the volumetric displacement variation behavior of the hydraulic motors. The displacement of pump M_p ramped up and down frequently with the flow rate. It also indicated that the swash plate can be altered by cylinder cy_2 instantaneously and ensure a relative constant power output. Frequent changing volumetric displacement of pump between maximum and minimum is not conducive to extend the life of hydraulic components, however. This needs to meet the requirements of higher reliability of pump. Oncoming investigations will be looking into this.

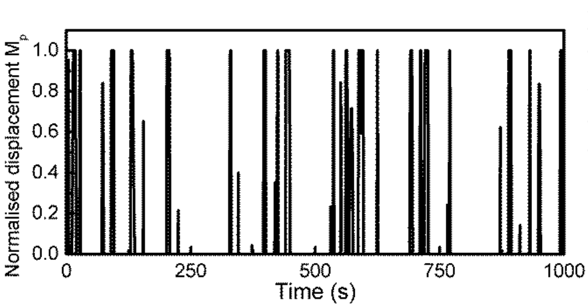

Fig. 8: Relative displacement of the pump M_p

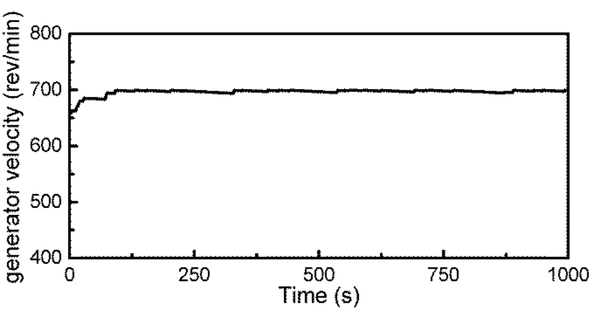

Fig. 9: Shaft velocity of generator

The generator velocity is demonstrated in Fig.9. Under the effect of hydraulic power decoupling and buffering of hydraulic accumulator a somewhat stabilized generator speed is achieved, that is, from 650 (rev/min) to 700 (rev/min). As a result, the constant frequency and stabilized voltage output become possible.

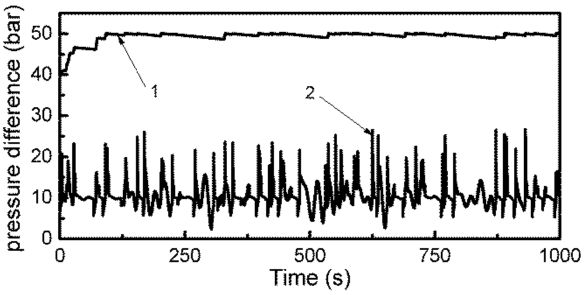

Fig. 10: Pressure difference between two chambers of motor M_1 and pump M_p

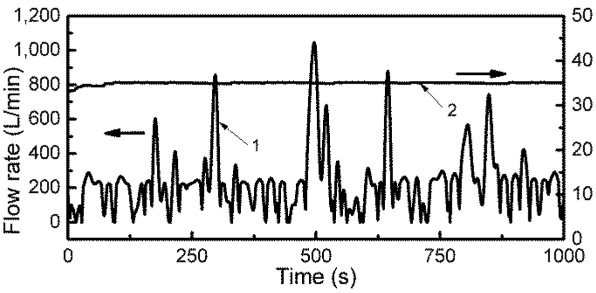

Fig. 11: Output flow of motor M_1 and pump M_p

Fig. 10 demonstrate the pressure difference between two chamber of motor M_1 and pump M_p and Fig.11 shows the output flow rate of them. It is clear that under the activity of hydraulic transformer input power represented by low pressure and high flow rate is converted into output power of high pressure and small flow rate. At the same time a variable hydraulic circuit is converted into a constant circuit.

5. Conclusion

In this paper, a scheme of hydraulic PTO system in wave energy converter (WEC) based on hydraulic transformer is proposed to solve the input-output power coupled problem in WEC. The input-output power decoupling is achieved by converting variable hydraulic circuit of low pressure and high flow rate into constant circuit of high pressure and small flow rate. The working principle and system composition present in the paper. A mathematical model is setup and simulation is performed to study the responds of PTO system under typical sea state. Simulation results show that it is possible to obtain a smooth power output from a WEC.

6. Acknowledgements

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