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Novel Design of Speed-increasing Compound Coupled Hydro-mechanical Transmission on Tidal Current Turbine for Power Generation

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Abstract. A key topic discussed in the energy industry has long been how to steadily convert tidal energy into mechanical energy and then electrical power. Gear transmissions are widely used in mechanical systems for electrical power production, converting low-speed input rotation into high-speed output rotation to drive a generator rotor. However, to achieve a large speed ratio and stepless speed change, gear transmissions must be accompanied by complex structures and high-precision manufacturing technology. The application of gear transmissions in tidal energy power generation must therefore come at a high cost. A large speed ratio and stepless speed-changing capability are precisely the two essential elements of the mechanical system for tidal energy power generation. In this paper, a new type of speed-increasing CCHMT has been proposed that is capable of achieving large transmission ratio speed change between the blade rotor input and the generator rotor output. It is also capable of changing the input speed steplessly into a stable output speed suitable for power generation and for high-quality electric power production. To verify the feasibility of using a speed-increasing CCHMT in tidal energy, a simulation model has been established for the wave power at the input end. With the assistance of a volumetric speed-control system and hydraulic accumulator, the speed-increasing CCHMT can stably transmit disordered input speed. Simulation results show that the output rotational speed gained a stable amplification ratio within 20 and 30. The mean square error of the rotational speed was controlled to within 29 and the output speed is limited within 85% to 115% of the average output speed, thus ensuring the quality of power generation.

1 Introduction

Ocean occupies the majority of the Earths surface and receives much more solar radiant energy than land does. According to data provided by UNESCO, the Worlds oceans hold almost 80 billion kilowatts of renewable energy, including wave energy, current energy, tidal energy, temperature difference energy, and salt difference energy [1][2]. Among these, the ocean tidal energy reserve is immense and its development technology is relatively mature, so it is one of the hotspots in todays pursuit of new energy sources. Tidal energy is a renewable energy derived from the periodic rise and fall of ocean water due to the gravitational force of the sun and moon [3]. The modern way of exploiting tidal energy is to use it in electric power generation [4]. The difference between tidal energy and other renewable energy is that tidal energy has a high energy density and is predictable and stable. Today's mature tidal power generation mode is the reservoir mode [5] that involves the construction of dams, sluices, and plant buildings near gulfs or bays and the installation of generator assemblies. Reservoir-type tidal energy power generation has a number of drawbacks: dams require large investment and maintenance and sedimentation issues are difficult to solve, among others. These problems greatly hamper reservoir-type tidal power generation and cause enormous ecological damage to the local area [6].

Today, gearboxes are widely used in speed control of tidal power generation equipment, but their stability is a problem yet to be solved [7]. Another available transmission mode is hydraulic transmission. Compared to mechanical transmission, hydraulic transmission has speed-modulation characteristics, especially in providing high-speed, low torque constant output from variable input of low speed and high torque [8]. However, a distinct drawback of hydraulic transmission is its low efficiency (approximately 70% compared to 90% for mechanical transmission [9]). Todays two popular research topics in tidal energy are hydrodynamics and power control [10]. The capturing device for tidal energy is usually a turbine device [11]. The hydrodynamic characteristics of tidal energy turbines mainly include torque characteristics, thrust characteristics, power characteristics, stall characteristics, cavitation characteristics, and flow-field characteristics [12]. These characteristics have a major effect on the efficiency and

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stability of the system. In-depth studies are being conducted by universities in various countries, and the research on maximum power control includes mainly two aspects: First, when the flow speed of water is low and cannot reach the rated speed, the power generation system tries to extract more energy from the tide and strives to operate by tracking the maximum power point. Second, when the flow speed of water is too high, the system can maintain its stability and simultaneously provide a stable power output and safe, stable system operation [13]. In actual operating conditions, the rotation speed of the rotor is often not optimal, so it is important to employ a transmission mode that regulates the speed of the rotor.

In a real situation, tidal energy is not stable; that is, the speed of the tide flow is not a constant at different times. This leads to great difficulties in the operation of the generator bus-bar assembly and in the integration into the power grid. This is highly detrimental to tidal energy power generation. To date, there have been few studies on the technology of controlling the maximum power of a tidal energy power generation system [14][15], but currently available wind power systems may serve as a reference. In the past, maximum power control is mainly achieved by the variable-speed, constant-frequency technique. The electrical energy conversion unit of wind power generation systems typically include a variable-speed generator, rectifier, inverter, and controller. In reality, the control of generation systems using this technology is quite di cult. Because the energy acquired is proportional to the third power of the flow speed, the control of this technique is very di cult. In a compound hydraulic and mechanical transmission, an auxiliary power device may be added to achieve energy compensation. This can effectively raise the energy collection efficiency and improve the stability of energy.

Undoubtedly, the tidal turbine blade structure and tidal turbine's design are very important to the whole energy system [16]. However, in this paper, the main focus is on the transmission system, because it is the key factor to operation efficiency. The speed-increasing compound coupled hydro-mechanical transmission (CCHMT) tidal energy power generation system introduced in this paper can perform well in an unstable flow field as described above. Unlike the floatable tidal energy converter model, in this study, the speed-increasing CCHMT tidal energy power system is equipped on some marine workplace as individual power source [17]. By adjusting the open degree of the volumetric speed control system of the CCHMT in real time, the system can vary the output speed in real time according to the changes of the tidal flow and keep the fluctuation of the output speed to within a small range. As a result, the peaks and valleys of the output rotational speed is smoothed out and the power generation rotor can operate better. The speed-increasing CCHMT can regulate the speed in a stepless manner and provide a continuously varying transmission ratio in a real transmission. Because natural tides pulsate and are unstable, the output rotational speed of the capturing device of the tidal energy is also not a constant. As a result, conventional speed-varying methods are unsuitable for tidal energy power generation systems. The development in speed control is to achieve stepless speed regulation based on variation of the speed.

In our previous research, we described the application of a CCHMT in heavy-duty vehicles. A CCHMT system can convert the high-speed rotation of the generator into output at high transmission ratio using the coupling between the mechanical system and hydraulic system. Conversely, in the application of tidal energy power generation, the CCHMT system can act as a speed-increasing device and convert the low speed into high-speed output through mechanical and hydraulic coupling. More significantly, the speed-increasing CCHMT, like the CCHMT that we used in heavy-duty vehicles, can also stabilize the rotational speed. As the tidal speed changes with time, so does the input speed of the tidal blades. When transitioning into the speed-increasing CCHMT through a clutch, we may change the open degree of the hydraulic system in real time to achieve speed stabilization; that is, as the tidal speed fluctuates,
the output speed can be stabilized by varying the open degree of the hydraulic system in real time, thus reducing subsequent difficulties as power enters the grid.

To verify the validity of the tidal energy power generation system described here, a simulation test was designed. The primary goal of the simulation is to test whether the speed-increasing CCHMT can stably amplify and ballast the rotational speed of the blade rotor of the tidal energy machine and obtain a higher output speed with less fluctuation. The entire simulation process was carried out with the AMESim software of Siemens. The input end was modeled according to the ocean current equation and, to verify the stabilization and ballast effect of the speed-increasing CCHMT on the flow, the experiment set up an unstable rotational speed on the input end of the rotor (the rotational speed fluctuates randomly, but only within a certain range, due to the specific wave equation source and ocean current equation results plus the effect of random factors). The ocean current machine discussed in this paper is situated mainly under the ocean waves. Owing to the large amplitude variation of the hydrodynamic force within the wave cycle, this type of wave condition is more suitable for the participation by the speed-increasing CCHMT. Disregarding the effects of extreme weather, the wave cycles are distinct and can be accurately predicted.

This paper is organized as follows: Section 2 describes the basic configurations of ocean wave equations as well as the transmission's basic characteristic. Section 3 presents the simulation of a tidal current generation with speed-increasing CCHMT. Conclusions are shown in Section 4.

2 Analysing of turbine's working condition and transmission model

Similar to wind power generation, due to the randomness, fluctuation and intermittence of ocean currents, the power quality of tidal power generation has strong uncertainties such as randomness and fluctuation, and such instability will inevitably have a significant impact on the safety of power grid [18].

The output hydrodynamic characteristics of the tidal machine are distinctly periodic. In the cycle of one revolution, the power coefficient and thrust coefficient of each blade go through one cycle of change. On the whole, the power coefficient and thrust coefficient have three periodic changes within one rotational cycle as far as the entire rotor is concerned. The uneven load condition will have an effect on the stable operation of the tidal machine. Operating under the ocean waves, the hydrodynamic characteristics of the tidal machine experience periodic changes during one cycle of revolution and one wave cycle. In one wave cycle, there are large amplitude changes in the hydrodynamic force on the tidal machine.

A proper analysis of the hydrodynamic characteristics can guide the control and safe operation of the tidal machine. Disregarding the effect of extreme weather, the periodicity of the waves is distinct and can be accurately predicted. The wave model parameters given in this paper are for the mix conditions of waves in the English Channel and southern Irish Sea [19][20].

2.1 Introduction of ocean wave model

The text of your paper should be formatted as follows:

Table 1. Nomenclature1.

λ_0	Tidal current generation's turbine Tip speed ratio
ω	Tidal current generation's turbine blade speed
R	Tidal current generation's turbine blade tip radius
V	Tidal current generation's tidal current velocity
P	Tidal current generation's turbine blade captured power
C_p	Tidal current generation's turbine power Coefficient
L	Ocean water wavenumber
C_d	Ocean water depth
g	Gravity acceleration
ρ	Ocean water density

To establish the model of turbine generating, it is quite necessary to provide the basic parameters of tidal stream turbine generator. Initially, the tip speed ratio(TSR) must be determined, which describes the relationship between the velocity of fluid before it flows through the turbine blade, the turbine blade speed and the turbine blade tip radius.

$$\lambda_0 = \omega R / V \tag{2.1}$$

In this study, the simulation test of the speed-increasing CCHMT is using the design of blade of the tidal turbine according to reference 2. Moreover, the velocity of fluid before it flows through the turbine blade will be described by the third-order Strokes nonlinear wave equation in order to simulate the dynamic seawater wave model. Eq. 2.2 shows the calculation method of turbine power coefficient which can be used to determine the tidal turbine's input power. Then, the input power equation can be described as Eq. 2.3.

$$C_p = \frac{P}{\frac{1}{2}\rho\pi V^3 R^2} \tag{2.2}$$

$$P = \frac{1}{2} C_p \rho \pi V^3 R^2 \tag{2.3}$$

According to the Eq. 2.3 tidal current speed V is the only unknown parameter. In this model, V is the current speed along with the x axis, in other word, $V = u_x$.

$$u_x = c\sum_{n=1}^{3} F_n \cosh nk\left(z+d\right)\cos n\left(kx-\omega t\right) \tag{2.4}$$

u_x, according to the third-order Strokes nonlinear wave equation can be described as Eq. 2.4 [21] , where c is tidal current wave speed and c can be determined by Eq. 2.5.

$$c = \sqrt{\frac{gL}{2\pi}\tanh kd\left[1+\left(\frac{2\pi a}{L}\right)^2 \frac{14+4\cosh^2 2kd}{16\sinh^4 kd}\right]} \tag{2.5}$$

In Eq. 2.5, parameter a is determined by value of tidal current wave height H and kd , where k is wavenumber and d is water depth. According to Eq. 2.6 and Eq. 2.7, a can be determined.

$$H = 2a + a\frac{\pi^2}{L^2}a^3 f_3\left(\frac{d}{L}\right) \tag{2.6}$$

$$f_3\left(\frac{d}{L}\right) = \frac{3}{16}\frac{1+8\cosh^6 kd}{\sinh^6 kd} \tag{2.7}$$

In addition, according to what has been discussed above, the third-order Strokes nonlinear wave equation's multinomial coefficients $F_n\left(n=1,2,3\right)$ can be determined by Eq. 2.8, Eq. 2.9 and Eq. 2.10. Moreover, the wave period T also can be determined and it has been shown in Eq. 2.11.

$$F_1 = \frac{2\pi a}{L}\frac{1}{\sinh kd} - \left(\frac{2\pi a}{L}\right)^2 \frac{\left[1+5\cosh^2 kd\right]\cosh^2 kd}{8\sinh^5 kd} \quad (2.8)$$

$$F_2 = \frac{3}{4}\left(\frac{2\pi a}{L}\right)^2 \frac{1}{\sinh^4 kd} \quad (2.9)$$

$$F_3 = \frac{3}{64}\left(\frac{2\pi a}{L}\right)^3 \frac{11-2\cosh 2kd}{\sinh^7 kd} \quad (2.10)$$

$$T = \sqrt{\frac{2\pi L}{g\tanh kd\left[1+\left(\frac{2\pi a}{L}\right)^2 \frac{14+4\cosh^2 2kd}{16\sinh^4 kd}\right]}} \quad (2.11)$$

According to the TSR research from A.S. Bahaj[22][23], when the turbine power coefficient reaches 0:4, the value of TSR will be 4. However, because of energy loss, in the real seawater working condition, the value of TSR is lower than tested value. Therefore, in this study, the value of TSR is 3. Considering those equations above, the tidal current speed curve based on the third-order Strokes equations can be depicted. However, according to the tidal current simulation, this kind of ideal curve is not able to provide valuable instruction for practical working condition, and it cannot provide reliable experimental data in the progress of the simulation. In fact, the real tidal current working condition is effected by various forms of random factors and thus it cannot be predicted accurately. Accounting on these effects, in this study, the ideal third-order Stokes tidal current curve has been improved by adding the random noise curve in order to predict and simulation the working condition as accurate as possible.

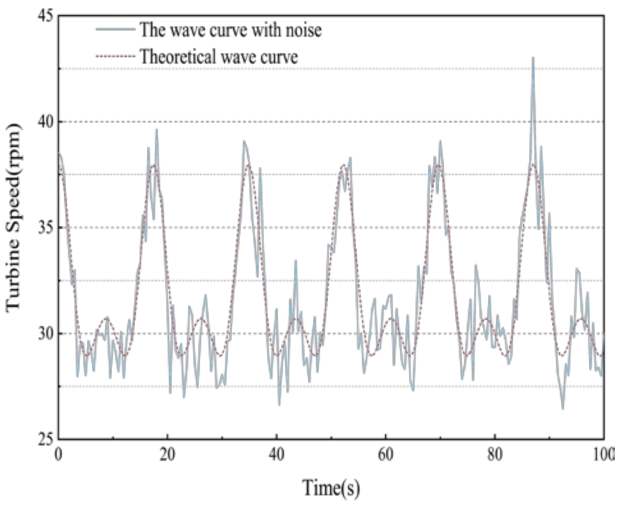

Fig. 1. Third-order Strokes nonlinear wave equation and wave with random noise.

A tidal machine is a classical fluid rotation machine. Eddy-current field structures will form at the end of the flow field, with pronounced effects on the rotor situated downstream of the flow field. However, the effects of the end flow field can be reduced, and the spatial utilization rate of the tide and dynamic energy conversion efficiency are improved by properly setting the rotational speed between the upstream and downstream rotor, and by properly setting the separation distance between the rotors. According to the simulation data, the single power of tidal power generation is 1.5552MW which is calculated with the assistance of the formula in this paper. Obviously, it is consistent with the power of the 1.5MW AR1500 turbine of the 398 MW Meygen tidal stream project in Britain. Consequently, the parameters set in this paper meet the feasibility of the project [24].

2.2 Introduction of speed-increasing CCHMT

Table 2. Nomenclature2.

A_1	Characteristic parameter of the engine and planetary line
A_2	Characteristic parameter of the vehicle and planetary line
Ω_1	Input axis‘s speed
Ω_2	Output axis`s speed
i_0, i_1, i_2, i_3	Each outer gearing transmission ratio
i_g	Mechanical transmission’s ratio of speed-increasing CCHMT
e	Displacement ratio
i_{HM}	Total outer transmission’s ratio of speed-increasing CCHMT

The speed-increasing CCHMT has two main components: a mechanical system centered on a planetary gear train and a hydraulic system centered on a volumetric speed-regulating circuit, those two main components provides both advantages to the system. The mechanical system of the planetary gear train ensured that the speed-increasing CCHMT has a large basic transmission ratio [25] so that it can convert a low-input rotational speed into a high-output rotational speed. Since the transmission is achieved through the meshing of gears, its efficiency is high and the energy loss is low. However, the entire tidal energy power generation system must have a stable rotational speed, and itis difficult to achieve the conversion from a variable input speed to a stable output speed by relying on only one mechanical system.

After the input speed enters the speed-increasing CCHMT through a clutch converter, it is divided into two parts, one part entering the mechanical system of the CCHMT and the other entering the volumetric speed control circuit of the hydraulic system. The output speed of the volumetric speed-control system re-enters the mechanical system through the planetary gear train [26]. The speed regulation ratio of the volumetric speed-control circuit of the hydraulic portion can be changed in real time, and the speed ratio of the speed-increasing CCHMT can be changed at any time by strategically changing the open degree. According to our former research [27] shown in Fig. 2, the total outer transmission's ratio of CCHMT i_{HM} follows Eq. 2.12, where $i_g = i_0 i_1 i_2 i_3$.

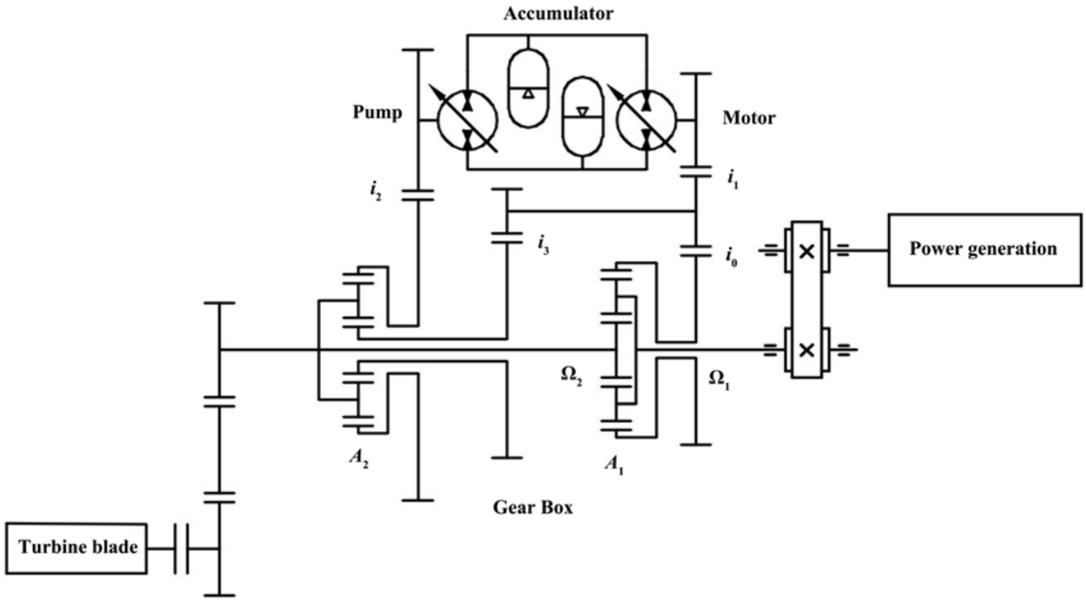

Fig. 2. CCHMT's kinematic scheme.

$$i_{HM} = \frac{\Omega_2}{\Omega_1} = \frac{i_1 i_2 + A_2 e i_3}{(1 + A_1)(i_1 i_2 + A_2 e i_3) - A_1 (1 + A_2) i_g} \tag{2.12}$$

The difference between a speed-increasing CCHMT and other hydro-mechanical transmissions is that a speed-increasing CCHMT has a volumetric speed-control system and a set of sack-type accumulators. As the volumetric speed-control system begins its function, high-pressure flow enters the accumulator and energy is stored. In a speed-increasing CCHMT, the energy in the accumulator may be viewed as an auxiliary energy source to assist the starting and braking of the rotor. When the tide flow acts on the blades, there is a direct proportionality relationship between the speed of the ocean wave and the rotational speed of the blades. The variation of wave speed within a certain range causes variation of the blade speed within a certain range (with a certain phase difference).

In using tidal energy for power generation, it is desired that the output rotational speed maintains a low-level fluctuation within a small range, which would be beneficial for the quality of the power generated. As the speed of ocean wave fluctuates, the volumetric speed-control system and accumulator play the role of ballast; that is, when the speed of the ocean wave exceeds a certain range, the open degree of the variable pump in the volumetric speed control system changes, thereby changing the displacement of the variable pump. In addition, with the assistance of the regulating function of the accumulator, the CCHMT of the tidal energy power generation system is capable of adjusting to the fluctuation of the input speed within a range.

3 Simulation of tidal current g-eneration with speed-increasing cchmt

To verify the validity of the tidal energy power generation system described here, a simulation test was designed. The primary goal of the simulation is to test whether the speed-increasing CCHMT can stably amplify and ballast the rotational speed of the blade rotor of the tidal energy machine and obtain a higher output speed with less fluctuation. The entire simulation process was carried out with the AMESim software of Siemens. The input end was modeled according to the ocean current equation and, to verify the stabilization and ballast effect of the speed-increasing CCHMT on the flow, the experiment set up an unstable rotational speed on the input end of the rotor. Generally speaking, the rotational speed fluctuates randomly, but only within a certain range, due to the specific wave curve source shown in Fig. 1 and ocean current equation results plus the effect of random factors[28].

The ocean current machine discussed in this paper is situated mainly under the ocean waves [29]. Owing to the large amplitude variation of the hydrodynamic force within the wave cycle, this type of wave condition is more suitable for the participation by the speed-increasing CCHMT. Disregarding the effects of extreme weather, the wave cycles are distinct and can be accurately predicted.

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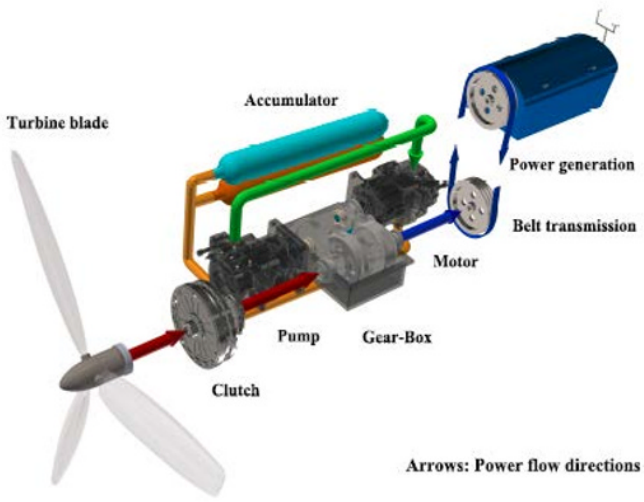


Fig. 3. Speed-increasing CCHMT schematic diagram.

Tidal current power generation system based on speed-increasing CCHMT has been depicted in Fig. 3. When turbine blade harvests the tidal energy, it will transform from fluid kinetic energy into mechanical kinetic energy. Then, mechanical kinetic energy is transmitted to power generation through converter, speed-increasing CCHMT and belt drive system. During this process, the revolving speed has been increased which is able to meet the power generations required working speed. The accumulator in this transmission can resist sudden fluctuation from the ocean current by switching on and switching off the accumulator according to system control strategy.

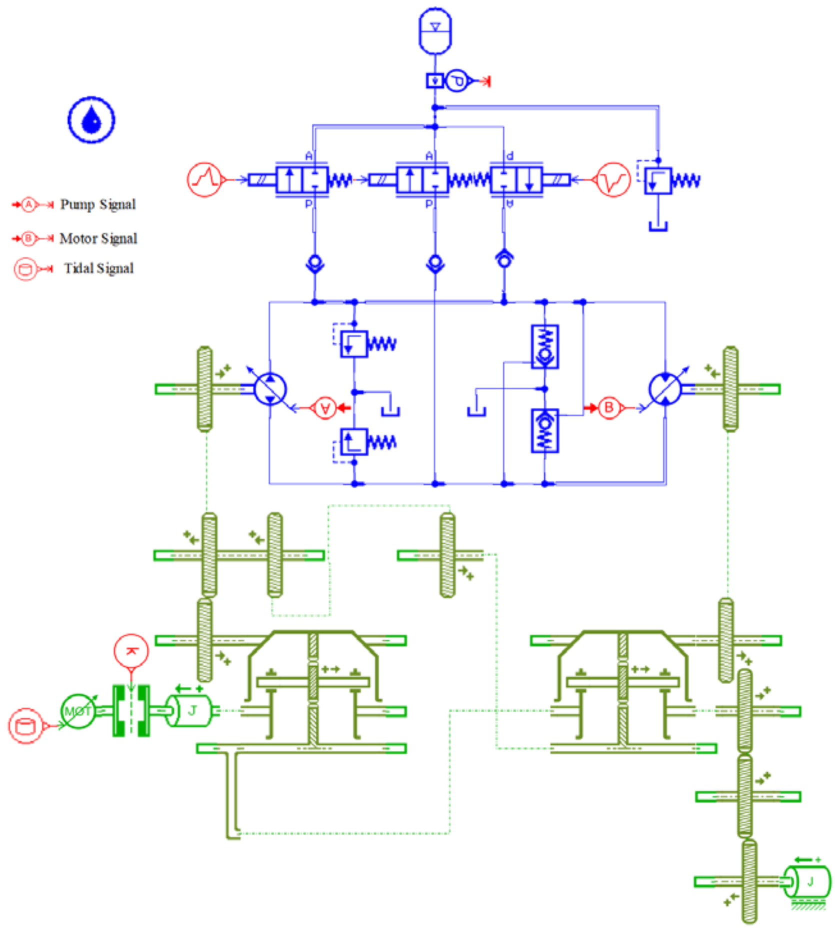
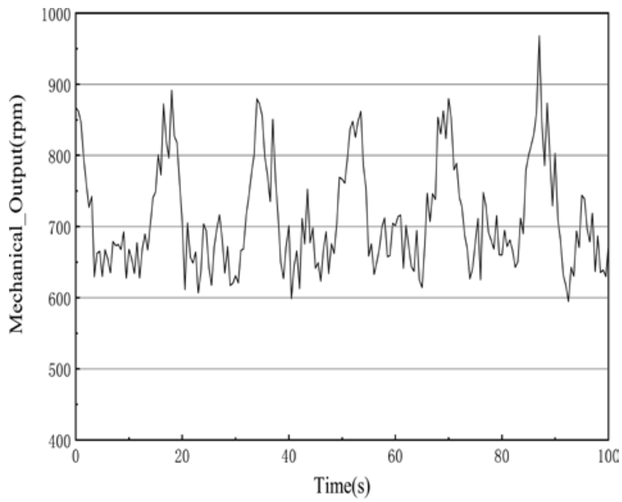
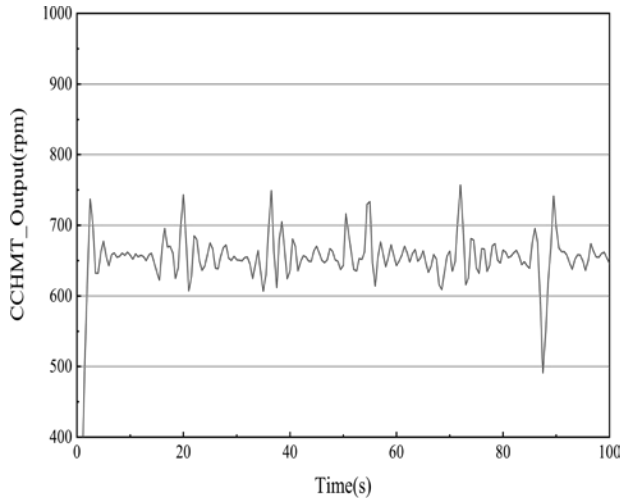


Fig. 4. The AMESim simulation model for analyzing tidal current generation with speed-increasing CCHMT is depicted. The main part shows the transmission system's structure and signal sources.

The speed-increasing CCHMT system proposed here for tidal energy power generation can provide a speed boost at high transmission ratio within 20 and 30 and accommodate input speeds with a wave nature. According to the preceding section, an AMESim model has been established with the assistance of those equations above [30]. As is depicted in Fig. 4, the transmission structure model and the connection between the mechanical and hydraulic components are clearly shown in this figure. At the beginning of the simulation, the random wave speed equation has been coded into the input end of the model. As for the compund coupled hydraulic mechanical transmission, the output speed varies from 0 rpm. Compared to the mechanical transmission, the CCHMT has a little delay because of the hydraulic hysterisis effect. Obviously, the output speed from CCHMT has less fluctuation than the traditional mechanical transmission. The simulation consequences are depicted in Fig. 5(a) and Fig. 5(b).

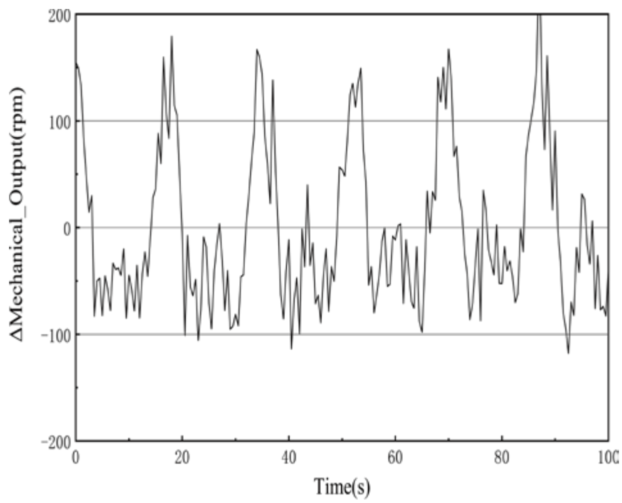


(a) Mechanical transmission.

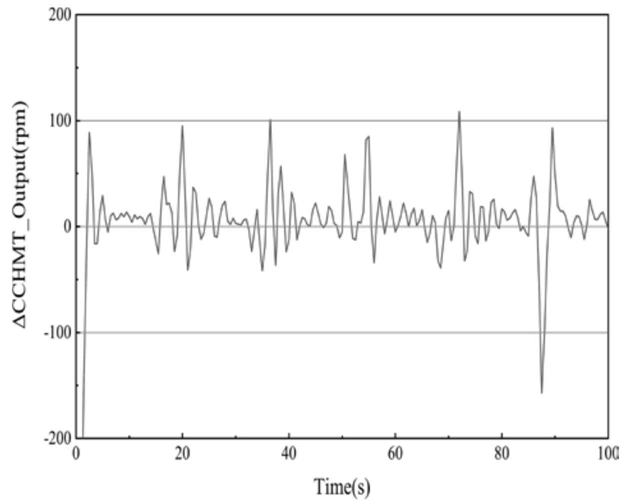


(b) Speed-increasing CCHMT

Fig. 5. The output speed of transmission.



(a) Mechanical transmission.



(b) Speed-increasing CCHMT.

Fig. 6. The deviation of output speed from the mean speed.

With the assistance of a hydraulic volumetric speed-control system and hydraulic accumulator, the speed-increasing CCHMT can provide stable regulation of the input speed of the generator rotor in tidal power generation. The fluctuation of the output rotational speed can be maintained in a small range and the quality of the generated power can be assured.

As is shown in Fig. 6(a) and Fig. 6(b), the output speed from speed-increasing CCHMT has less fluctuation that from mechanical transmission. According to the output speed curve, speed-increasing CCHMT's output speed varies in a comparably small range which means tidal current generation with speed-increasing CCHMT can adapt the random ocean wave and generate electricity in high quality [18]. To analyze the data in Fig. 5(a) and Fig. 5(b), the mean square errors are 76:4 and 29:0. As a consequence, according to figures, it is easy to draw the conclusion that tidal current generation with speed-increasing CCHMT can work under the comparably stable speed that is the output speed is limited within 640 rpm to 740 rpm which is suitable for tidal current power generation.

4 Conclusions

The speed-increasing CCHMT system proposed here for tidal energy power generation can provide a speed boost at high transmission ratio and accommodate input speeds with a wave nature. With the assistance of a hydraulic volumetric speed-control system and hydraulic accumulator, the speed-increasing CCHMT can provide stable regulation within 20 to 30 of the input speed of the generator rotor in tidal power generation. The fluctuation of the output rotational speed can be maintained in a small range which the mean error of the output speed is 29:0 and the output speed is limited within 85% to 115% of the average output speed, in another word, the input speed of the tidal current generation grid changes in a small variation and makes the power grid electric parameters easy be controlled. Therefore, the quality of the generated power can be assured. The basic structure of the speed-increasing CCHMT has been designed and the experiment platform has been already built. In the future, this research will focus on optimization of the control strategy and provide more data to verify the feasibility of this project.

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