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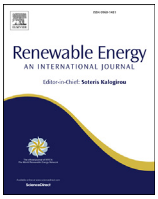

Speed control of oil-hydraulic power take-off system for oscillating body type wave energy converters

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ABSTRACT

The variable displacement oil-hydraulic pumps for the Power Take-Off (PTO) of wave energy converters must work above 80% of maximum displacement in order to have an overall efficiency of approximately 94.5%. This is achieved by controlling their rotational speed when the oil-hydraulic power fluctuates in time. Three speed control strategies have been presented, the first fixing the maximum possible speed in each sea state, the second by slowly varying the pump speed between speed peak values and average ones, and the third by working with highly variable speed reference values. The worst pump efficiency is achieved with the first strategy while the best one with the third strategy. However, the first has less impact than the third one in the pump lifecycle. On the other hand, the second strategy is used to make a trade-off between pump efficiency and lifecycle. However, this paper presents a fourth speed control strategy, which is a hybrid of the second and third strategies. So, the objectives of this paper were to know if these strategies are implementable in a test rig and also on a new PTO concept and determining what modifications should be introduced in these PTO strategies and hardware. This paper also contributes with the application of new methodologies in this field of research for the modelling of pump efficiency and pressure control, such as Neuro-Fuzzy modelling and Fuzzy Logic control systems.

1. Introduction

The wave energy is transformed into electrical energy through two important phases, energy extraction and conversion. The wave energy extraction phase is made by allowing the ocean waves to act on bodies and then capturing mechanical and oscillatory energy of the buoy. There is a large quantity of extraction concepts but they can be classified into three different types of devices, known as point absorber, attenuator and terminator Wave Energy Converter (WEC) devices. This classification is based on their shape and orientation towards the incoming waves. Reviews of these concepts can be found in Drew et al. [1], Falcão [2] and Guedes Soares et al. [3]. On the other hand, the mechanical and oscillatory energy is converted into electrical energy with Power Take-Off (PTO) systems [3]. There are also different technologies implemented in these PTOs. The most promising technology is the oil-hydraulic one, because it is suitable for the transmission of large power and torque with low-frequency waves and has a fast frequency response [1,4]. Moreover, this technology can be effectively used to tune the WEC in order to maximize wave energy extraction. This is carried out with the continuous phase control of the WEC movement [5–8], or in other words, positioning the WEC oscillatory velocity in phase with the excitation force of the wave [9].

The oil-hydraulic PTO has been developed in order to achieve the best conversion efficiencies and to boost the wave energy extraction performance for a range of irregular sea states. Thus, the architecture of the hydraulic PTOs has evolved from initial concepts to solve technical problems such as rectification, stabilization and conversion of the oscillatory energy into others to improve the conversion efficiency for different sea states, and ultimately to more sophisticated ones to boost wave power extraction. A review of these concepts is presented by Gaspar et al. [10], where a new PTO concept is also presented which is able to adapt to different types of WECs with reliable, standardized and scalable oil-hydraulic technology.

This paper presents a real test of the speed control strategy of

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the PTO presented and simulated by Gaspar et al. [10–12] since similar studies in this subject are also based on simulations [13–15]. In both cases the PTO efficiencies are achieved by controlling the rotational speed of the oil-hydraulic pumps however, and in particular in Gaspar et al. [10], the technological limitations of speed control in a real case scenario are not considered. So, the objectives of this study were to know if PTO pump speed control strategies are implementable in a test rig, what modifications should be introduced in these strategies and PTO hardware, in particular, which components are more adequate to deal with the rotational accelerations demanded by these strategies.

This paper is organized in five sections. In Section 2 the PTO concept, its main features and a preliminary comparison with the state-of-the-art is presented. The modelling of this PTO and the preliminary numerical simulations are made for three irregular sea states and are presented in Section 3. These simulations are analyzed in order to set the requirements for a real test in the Tecnalia PTO test rig, as described in Section 4. The results of these tests are presented and discussed in Section 5 and then summarized in the conclusion.

2. PTO concept

The PTO concept presented by Gaspar et al. [10–12] is an architectural evolution of the one presented by Hansen et al. [15] and Hansen [16] for the Wavestar WEC, as presented in Figs. 1 and 2. However, the hydraulic layout presented in Fig. 2 is also an evolution of the Wavestar WEC design. Two new hydraulic circuits are added, the overflow and charging ones. The function of the overflow system is to by-pass flow into the overflow generator when the flow in the hydrostatic transmission exceeds the maximum flow of the four quadrant oil-hydraulic pump, which would in the original design be wasted in the pressure relief valves. On the other hand, the function of the charging system is to refill the hydrostatic transmission with the same flow that is discharged into the overflow system plus the leakage flows in the cylinder and four quadrant pump. The additional advantage of using this design is to avoid the oversizing of the four quadrant and generator units [15]. These units are also sized taking into consideration the more probable sea states and not the one that generates the peak power.

The adaptations made by Hansen et al. [15] on the original design are also extended to the control of the rotational speed of the hydraulic pumps. In the original design the generator and the hydraulic pump rotate at a fixed speed. Nevertheless, this has an implication on the overall efficiency of the hydraulic pump since its displacement is varied far from the full displacement in order to work with the flow of the hydrostatic transmission. According to Gaspar et al. [10–12] the overall efficiency drops significantly below 75–80% of full displacement. However, this problem can be minimized by keeping the pump displacement above 75% by adjusting its rotational speed with the electrical generator.

Two speed control strategies are proposed by Hansen et al. [15], simulated and compared with the fixed speed strategy (1500 rpm) in order to compare gains on the overall oil-hydraulic efficiency. In the first strategy the generator speed is slowly varied according to the average peak flow in the hydraulic transmission while in the second the speed is controlled in order to hold the pump displacement at 100%. However in both case studies a limit of 1000 rpm is set on the generator speed when operating at motor mode in order to avoid high consumption of electrical power to accelerate the generator inertia. The simulation results [15] have shown that the best efficiencies are achieved with both strategies, in particular the second one, however with implications on the components lifecycle. The first strategy should be adopted when the sustainability of the system is considered in the design process.

Fig. 1. Wavestar prototype [16].

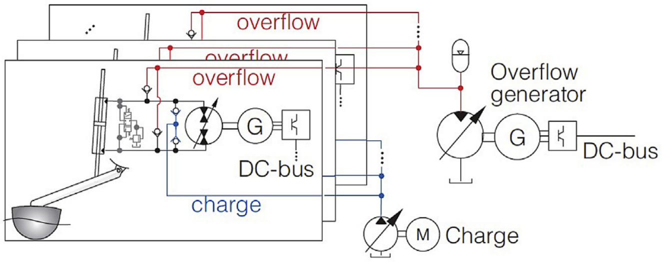

Fig. 2. Wavestar Power Take-Off [16].

The concept presented by Gaspar et al. [10–12] goes further in this attempt to increase the hydraulic efficiency of the four quadrant mode pump. A modified version of this concept is presented in Fig. 3. An electric drive is added in parallel with the secondary unit drive and the overflow and charging approach presented in Fig. 2 is added.

The objective of this concept is to use the electric drive only for reactive mode, or in other words, when the WEC peak velocity must be adjusted to be in phase with the wave excitation peak force. The reactive power is given by the kinetic energy stored in the drive with one fraction of the total extracted power while the main part of the hydraulic power is bypassed into the low pressure side of the system (pipeline *i*). These two operating modes are achieved by closing the pilot-to-close check valves (8 and 9) during the reactive mode and letting them open and subjected to the differential pressure between the high and low pressure circuits during the energy extraction mode.

So, the first advantage of this design is to reduce even more the size of the electrical drive, hydraulic pump (7), generator (17) and inverter (16), by bypassing even more power through the overflow circuit and minimizing the operation of the generator in the motor mode with high power consumption. The second advantage is to improve the speed control strategies and the lifecycle of the drive components, because much less power is handled than in the Hansen et al. design [15].

In Fig. 3 an optional transformation unit (7 and 10) added to the pipeline (*i*) is also presented. The main advantage of this solution is to avoid the extra inefficiency added by the inverter (16) and to benefit from the cooling effect provided by the oil, which is hard to achieve in an electrical generator by itself when running at slow speeds. There are also no speed limitations during motor mode and this unit takes less space than generator and inverter together, resulting in a compacter PTO.

Despite all these advantages these speed control strategies were