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Modeling and control of a hybrid wind-tidal turbine with hydraulic accumulator

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ABSTRACT

This paper presents the modeling and control of a hybrid wind-tidal turbine with hydraulic accumulator. The hybrid turbine captures the offshore wind energy and tidal current energy simultaneously and stores the excess energy in hydraulic accumulator prior to electricity generation. Two hydraulic pumps installed respectively in wind and tidal turbine nacelles are used to transform the captured mechanical energy into hydraulic energy. To extract the maximal power from wind and tidal current, standard torque controls are achieved by regulating the displacements of the hydraulic pumps. To meet the output power demand, a Proportion Integration Differentiation (PID) controller is designed to distribute the hydraulic energy between the accumulator and the Pelton turbine. A simulation case study based on combining a 5 MW offshore wind turbine and a 1 MW tidal current turbine is undertaken. Case study demonstrates that the hybrid generation system not only captures all the available wind and tidal energy and also delivers the desired generator power precisely through the accumulator damping out all the power fluctuations from the wind and tidal speed disturbances. Energy and exergy analyses show that the energy efficiency can exceed 100% as the small input speeds are considered, and the exergy efficiency has the consistent change trends with demand power. Further more parametric sensitivity study on hydraulic accumulator shows that there is an inversely proportional relationship between accumulator and hydraulic equipments including the pump and nozzle in terms of dimensions.

1. Introduction

With the increasing attention to global climate change, reducing greenhouse gas emissions has been more important in the electricity industry especially. Many energy researchers, government policy makers and industrial producers have increasing turned their interests to renewable energy generation, such as solar, geothermal, wind, wave and tidal [1–4]. Among those renewable energy, wind power has more commercially competitiveness and has been developed very fast, which could reach nearly 2,000 GW by 2030, supply between 16.7 and 18.8% of global electricity and help save over 3 billion tons of CO_2 emissions annually according to the last Global Wind Energy Outlook [5]. As the wind energy technology has become more and more mature, offshore wind has received significant attraction mainly due to two advantages: one is that the offshore wind is stronger and steadier than onshore wind and supplies a greater source reserves; the other is that the sea offers larger open spaces, so the bigger and more wind turbines can be installed. At present, the total capacity of offshore wind power has exceeded 7 GW, a large percent of which are installed in the North, Baltic and Irish Seas, the English Channel, China's east coast and Japan [5].

Recently, aiming to sustainably develop the offshore wind energy and efficiently utilize ocean resources, the integrated exploitations of offshore wind and ocean energy have been carried out by a number of researches [6,7]. Most of them concentrated on the ocean resource assessment and combined wave and wind energy extraction, for example, placing wave energy converters in the spaces of wind farms and using the same float platform and power cables, etc [8,9]. Nevertheless, other types of ocean energy such as tidal, thermal and marine current have rarely been involved in the integrated exploitations. In recent years, tidal current energy as an advantageous resource has been extensively studied, for its properties of high power density and quantifiability compared with wave and wind energies [10,11]. Existing devices designed to

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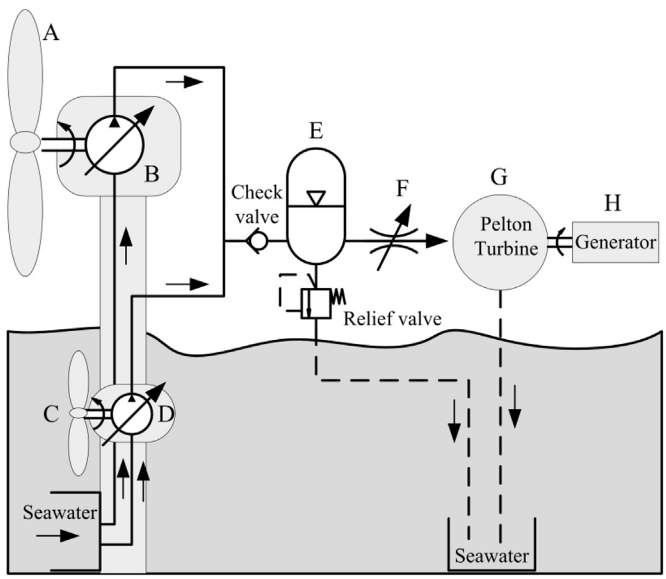

Fig. 1. Schematic of the proposed hybrid wind-tidal turbine system.

extract tidal energy include two forms: vertical and horizontal axis turbines [12]. No matter what kind of tidal machines, they function as underwater windmills, except their rotors are driven by currents and not the wind. Considering that tidal turbine follows the analogous principle as wind turbine, and the experience already obtained in wind turbine can be referred in the tidal turbine study [13]. So, combing one turbine with another is reasonable and feasible. Hence, a wind-tidal hybrid energy generation, in which a tidal turbine is incorporated into an offshore wind turbine electricity system, is proposed in this study. The schematic diagram of the hybrid system is shown in Fig. 1.

There are two major challenges in this study. The first one is how to economically and synergistically exploit the offshore wind and tidal energy. In the conventional wind turbine and tidal turbine, the gear boxes, the electricity generation, pressure-rise and incorporation components are installed in the nacelles [8]. So the conventional offshore wind turbine and tidal turbine only are combined with independent mechanical transmission and power generation systems but sharing the same support structures, operation and management personnel, grid connection and port structures, etc. But this type of combination increases the nacelle weight and leads to support structures vibration and fatigue load, as a result, more maintenance costs are needed [14]. So, a more economical and reliable hybrid approach is proposed, in which an open loop hydraulic drive in stead of the mechanical gear boxes is adopted to transmit energy, and the power generation systems are located on the down tower. This approach improves the reliability of the transmission system and decreases the loads on the support structures, thus the construction and repair costs are reduced. The good performances of hydraulic transmission in individual wind turbine or tidal turbine have been given in detail in the previous works of the authors [15], and the efficiency of hydraulic transmission is near 80% for both below and above rated wind speed conditions [16]. Further more, for the utilization of hydraulic transmission, the captured kinetic energy from wind and tidal is integrated as hydraulic energy prior to generation of electricity, the costs of power generation equipments are markedly decreased.

Another challenge is how to eliminate the unbalance between the electricity power generated from the hybrid system and the demand of users, because the intermittent and uncontrollable natures of the wind and tidal make the output power unstable and undispatchable. So an energy storage system is designed and applied in this hybrid system to provide steady and predictable output power. In the last decades, several energy storage systems including pumped hydro storage (PHS), flywheel energy storage system (FESS), compressed air energy storage (CAES), and so on [17,18], have been investigated and used to improve the renewable energy penetration level and power quality. Since the PHS and CAES are limited by geographical conditions and the short operation duration and high self-discharge losses are the main drawbacks of FESS, a hydraulic accumulator is adopted in this system as a more competitive option for energy storage system due to high power and energy density, fast response, simple maintenance requirement and economical consideration [15,19].

The purpose of the present study is to efficiently and economically develop the offshore wind turbine and tidal turbine. Thus, a hybrid renewable energy conversion system including a hydraulic accumulator is set up, and its dynamic performance and output power are analyzed in this paper. The other parts of this paper are organized as follow: firstly, the proposed system is described in Section 2. Then detailed mathematical modals, inertia dynamics, the control strategies, energy and exergy analyses are developed in Section 3, 4, 5and 6, respectively. Simulation results, energy storage analysis and discussions are performed in Section 7. Finally, conclusions are drawn in Section 8.

2. System overview

As shown in Fig. 1, a hybrid system including offshore wind and tidal turbine is developed. A variable displacement pump (B) is coupled to the wind turbine rotor (A) in the nacelle, through which seawater is pressed and flows in the hydraulic circuit. A tidal turbine (C) is attached to the spar body of the offshore wind turbine through a swinging arm under seawater. The swinging arm can be moved up for installation or maintenance. A variable displacement pump (D) is employed in tidal turbine (C) and plays the same role as which in wind turbine. A hydraulic accumulator (E), a nozzle (F), a Pelton turbine (G) and an induction generator (H) are connected in tandem to the two variable displacement pumps (B and C) in the open-loop hydraulic transmission. Fig. 2 is a block diagram showing the energy conversion of the hybrid wind-tidal turbine system.

3. Mathematical models

3.1. Wind turbine

The role of the wind turbine rotor is transforming the wind's kinetic energy into the mechanical energy of the rotor. The output power P_w and torque T_w of the rotor are expressed as [20]:

$$P_w = \frac{1}{2}\rho_{air}\pi R_w^2 C_{Pw}(\lambda_w, \beta_w)v_w^3 \tag{1}$$

$$T_w = \frac{1}{2}\rho_{air}\pi R_w^2 C_{Pw}(\lambda_w, \beta_w)v_w^3 \Big/ \omega_w \tag{2}$$

where ρ_{air} is the air density, R_w is the radius of turbine blade, v_w is the wind speed, ω_w is the wind turbine rotor angular speed, $C_{Pw}(\lambda_w,\beta_w)$ is the power coefficient of the wind turbine, in this study the power coefficient is expressed as [21]: