Energy Conversion and Management 110 (2016) 338–346

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Study on the application of energy storage system in offshore wind turbine with hydraulic transmission

Yajun Fan [a,b,*], Anle Mu [a], Tao Ma [a]

[a] School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China
[b] School of Mechatronic Engineering, Xi'an Technology University, Xi'an 710032, China

ARTICLE INFO

Article history:
Received 16 June 2015
Accepted 5 December 2015
Available online 30 December 2015

Keywords:
Offshore wind turbine
Fluid power transmission
Hydraulic accumulator
Pelton turbine

ABSTRACT

A novel offshore wind turbine comprising fluid power transmission and energy storage system is proposed. In this wind turbine, the conventional mechanical transmission is replaced by an open-loop hydraulic system, in which seawater is sucked through a variable displacement pump in nacelle connected directly with the rotor and utilized to drive a Pelton turbine installed on the floating platform. Aiming to smooth and stabilize the output power, an energy storage system with the capability of flexible charging and discharging is applied. The related mathematical model is developed, which contains some sub-models that are categorized as the wind turbine rotor, hydraulic pump, transmission pipeline, proportional valve, accumulator and hydraulic turbine. A linear control strategy is adopted to distribute the flow out of the proportional valve through comparing the demand power with captured wind energy by hydraulic pump. Ultimately, two time domain simulations demonstrate the operation of the hybrid system when the hydraulic accumulator is utilized and show how this system can be used for load leveling and stabilizing the output power.

1. Introduction

Wind power has now firmly established itself as a main steam option for new electrical generation [1]. In the past decades, especially, offshore wind turbine is received more attention, for the offshore wind is stronger and steadier than on shore wind. Current offshore wind turbine technologies are designed to address some new challenges, such as reliability, corrosion and maintainability. However, most of these technologies are based on traditional onshore turbines that have been modified to the offshore conditions. In the mechanical transmission system of the conventional turbine, variable ratio gearbox is used to provide energy for the shaft connected with a generator. Because the large scale gearbox is more apt to fail [2], regular repairs are required, which can considerably increase operation and maintenance costs. Although it also happens to onshore turbines, such maintenance in the offshore environment is more complex and expensive. Another point of concern in the existing transmission system is the use of vast amounts of copper. Nevertheless, copper price is very unstable and greatly affects the cost of manufacture of wind turbine [3]. Finally, with the moving of offshore wind turbine to more remote and deeper locations and the increasing of the size [4], the more mass and complexity will hinder the development of offshore wind turbine.

Recently, a concept to use a hydraulic-based transmission system as an alternative energy transfer technology is investigated [5], in which an entire hydraulic circuit or only a pump is place in the nacelle. This transmission system is more compact and lighter compared to gearbox or other drive train, so significantly reduces both the nacelle weight and the maintenance costs. Diepeveen and Laguna coming from Delft University of Technology, propose a new transmission system for wind turbine, where a hybrid closed-loop and open-loop fluid power circuit is used [6]. At the end of the circuit, pressurized seawater is pumped to a centralized hydroelectric conversion plant. Furthermore, detail analyses about dynamic performance of the proposed transmission system under different operational conditions are implemented by Laguna [7]. Aiming to evaluate the application of hydrostatic transmission in wind turbine from an energetic point of view, Silva et al. used numerical models to calculate the annual energy production for different drive train configurations including the conventional direct drive connection and advanced hydrostatic transmission, and so on. Finally, they found that the differences

* Corresponding author at: School of Mechanical and Precision Instrument Engineering, Xi'an University of Technology, Xi'an 710048, China. Tel.: +86 29 86173309.
E-mail address: fanyajunfan@sina.com (Y. Fan).

http://dx.doi.org/10.1016/j.enconman.2015.12.033
0196-8904/

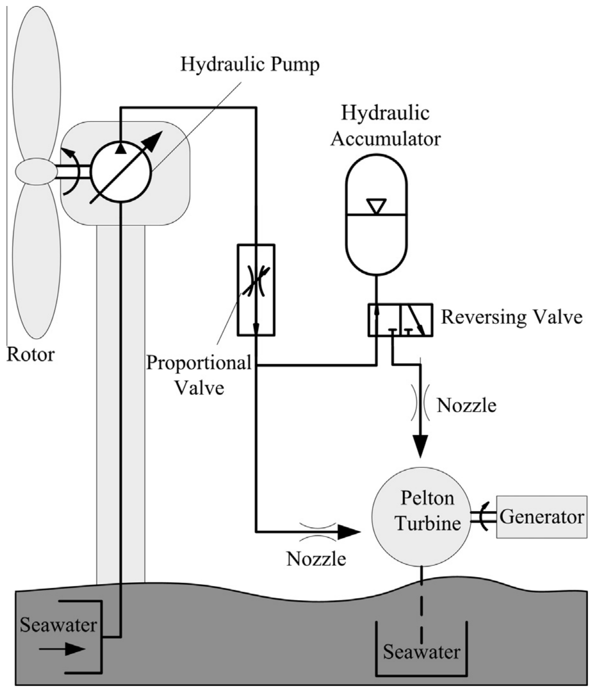

Fig. 1. Schematic of the proposed hydraulic wind turbine with an energy storage system.

among the investigated configurations are little (within 11.6%), but a hydrostatic transmission can improve system reliability, reduce the weight of the nacelle and cut the cost of maintenance [8].

It is generally known that the energy from wind is fluctuating and variable in nature and the stochastic nature make it difficult to integrate into a grid especially. In conventional wind farm with mechanical transmissions system, some energy storage systems have been investigated and applied, those are pumped hydro storage (PHS), flywheel energy storage system (FESS), compressed air energy storage (CAES), and so on [9]. 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, the hydraulic accumulator is adopted as a more competitive option for energy storage system due to high power and energy density, fast response, simple maintenance requirement and economical consideration [10]. However, recent researches about the utilization of hydrostatic transmission in wind turbine are mainly focused on the power efficiency or the system control [11,12], in which influence of random wind speed and the effect of energy storage system are rarely studied.

In the present study, an offshore wind turbine with a hydrostatic transmission is taken as research object, in which an open loop seawater circuit is used. In an attempt to mitigate the fluctuation of wind power and provide steady power, a hydraulic accumulator is applied, through which the surplus energy can be stored and released at low wind speed. Furthermore, the mathematical models of the system including the hydraulic accumulator are developed to understand its dynamics and validate the energy storage ideas. The schematic diagram of the proposed system is show in Fig. 1.

This paper is organized as follow: firstly, the proposed system is described in Section 2. Then detailed mathematical models and the control strategies are developed in Sections 3 and 4, respectively. Simulation results of a 5 MW offshore wind turbine are performed in Section 5. Finally, conclusions are drawn in Section 6.

2. System overview

As shown in Fig. 1, a hybrid system including energy storage system and a hydraulic wind turbine is developed in this study. A variable displacement pump is coupled to the wind turbine rotor in the nacelle, through which seawater is pressured and flows in the hydraulic circuit. For the fluctuation of wind energy, a proportional valve is used to regulate and control the seawater flow to steady the output power. After pressured seawater passes the proportional valve, it is distributed into two branches. One branch directly drives the Pelton turbine connected with a fixed induction generator; the other branch flows into an accumulator and is stored as hydraulic energy. The stored energy is released to drive the Pelton turbine when wind energy is insufficient.

3. Mathematical model

A steady state system model is considered and a number of numerical sub-models including the performance of the wind turbine rotor, hydraulic pump, pipeline, proportional valve, hydraulic accumulator and Pelton turbine are described in this section.

3.1. Wind turbine rotor

The role of the wind turbine rotor is transforming the wind's kinetic energy into the mechanical energy of the rotor. The optimum angular velocity of the rotor is expressed as a segmented function of the wind speed, and is given in equation (1). Furthermore, the output power and torque are calculated in equations (2) and (3), respectively. The segmentations correspond to different operating conditions of the wind speed, which are based on a control scheme in Refs. [13,14]. The control scheme pertaining to the original NREL reference turbine is neglected in this study.

$$\omega_{opt}(v_w) = \begin{cases} 0, & v_w < v_{in}, \quad v_w > v_{out} \\ \left(\frac{\lambda_{opt}}{R}\right) v_w, & v_{in} \leqslant v_w < v_{rated} \\ \left(\frac{\lambda_{opt}}{R}\right) v_{rated}, & v_{rated} \leqslant v_w \leqslant v_{out} \end{cases} \tag{1}$$

where ω_{opt}, λ_{opt} and R are optimum rotor angular speed, optimum tip speed ratio and the radius of turbine blade, respectively. v_w, v_{in}, v_{out} and v_{rated} are the wind speed, the cut-in wind speed, the cut-out wind speed and the rated wind speed, respectively.

$$P_{rotor} = \frac{1}{2}\rho_{air}\pi R^2 C_p(\lambda_{opt})\left(\frac{R\omega_{opt}}{\lambda_{opt}}\right)^3 \tag{2}$$

$$T_{rotor} = \frac{1}{2}\rho_{air}\pi R^2 C_p(\lambda_{opt})\left(\frac{R}{\lambda_{opt}}\right)^3 \omega_{opt}^2 \tag{3}$$

where P_{rotor} and T_{rotor} are output power and torque of turbine rotor. ρ_{air} and $C_p(\lambda_{opt})$ are the air density and the optimum power coefficient of the wind turbine.

3.2. Pump in nacelle

Here, a variable displacement pump installed in nacelle is used to pump high pressure seawater. Assuming that the shaft of the pump is perfectly coupled with the wind turbine rotor and the frictional losses is neglected. So, the relation between the pump and the rotor is given as:

$$\omega_{pump} = \omega_{opt} \tag{4}$$

$$T_{pump} = T_{rotor} \tag{5}$$